The Surfer and the Sea Lion:
A Conversation about Being

by

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Dedication

To my parents, Samuel Aaron Weiss, MD, whose appreciation of knowledge and beauty always inspired me, and Gladys Backer Weiss, RN, whose common sense and gentle wisdom still guide me.

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Brief Chapter Summaries

Prologue: Encounter. A surfer (Moses Hart) and a sea lion (Socrates) collide while surfing the same wave. Knocked semiconscious, the surfer is transported into a transcendent dream-like state in which the sea lion unexpectedly begins to speak to him.

PART I: Nature

Chapter 1: Old Soul. After apologizing for the collision, the sea lion introduces himself as an Old Soul or Muse who originally appeared before Plato in a human form as the Greek philosopher Socrates. He explains that he is now visiting the surfer Moses to discuss philosophy. They decide to begin with Protagoras's proposition that "Man is the measure of all things."

Chapter 2: The Sixth Sense. Socrates asks Moses to give him a modern scientific interpretation of "Man is the measure of all things," from which they arrive at the conclusion that logical reasoning, like sight, hearing, taste, touch and smell, must also have evolved biologically as a useful way to interpret the environment, but not necessary as a window into the true nature of reality. They discuss Plato's Myth of the Cave as a metaphor for the human condition, using the Three Body Problem (the inability of solving Newton's Laws of Motion analytically to predict planetary orbits in a solar system containing more than two bodies) as an illustration of the limitations of mathematics for describing reality with absolute precision.

Chapter 3: A Universe of Chaos. Expanding on the Three Body Problem, the discussion turns more generally to chaos in the mathematical sense, whose property of "sensitivity to initial conditions" (the butterfly effect) makes perfectly precise mathematical calculations unachievable. The logistic equation and weather prediction are used as illustrative examples. Socrates makes the point that even if mathematics were a perfect method for interpreting the physical world, the ability to predict future events with complete accuracy, in the Newtonian sense of a clockwork universe, is not possible when parts of the system are behaving chaotically.

Chapter 4: Quantum Weirdness. Following the discussion of chaos, a second nail in the coffin of obtaining a perfect knowledge about the Universe is highlighted by the fundamentally probabilistic nature of quantum theory. Socrates and Moses discuss wave-particle duality, the measurement problem, and the ongoing search for a Theory of Everything to unify gravity with the electroweak and strong nuclear forces. Leading proponents such as superstring and M theory that postulate bizarre concepts like hidden dimensions and multiple universes are discussed.

Chapter 5: Discerning Truth from Falsehood: Logic's Limits. The discussion turns to whether logical and mathematical reasoning are themselves perfect or suffer limitations in their ability to decide between truth and falsehood. Socrates points out that once nonlinearity (e.g. multiplication) is added into basic arithmetic, arithmetic and hence all of the other branches of mathematics that depend on it become incomplete. That is, rigorous mathematical statements analogous to self-referential versions of the Liar's Paradox like *"This statement is false"* can be constructed that cannot be proved either true or false (known as Godel's Incompleteness Theorem). Turing's seminal "Undecidability of Halting Theorem" is also described, and used as an example of how an esoteric problem can transform the world, in this case by conceptualizing the modern computer. The discussion then turns to how nonlinearity, despite its corrupting the ability of mathematics to always decide between truth and falsehood, is essential for describing behaviors like oscillations, switches, excitability, chaos, etc.) that serve as fundamental dynamical building blocks for everything in Nature.

Chapter 6: God Options. Ever the skeptical scientist, Moses continues to resist the idea that scientific reasoning is incapable of elucidating absolute truths about the nature of reality. When his initial arguments fail to persuade Moses that science may not be the ultimate answer, Socrates reveals his trump card. He points out that scientific reasoning is a method that derives conclusions from premises, and those premises are assumptions (ultimately axioms) that cannot be themselves be proven. They reach a consensus that even if science were to identify the most fundamental axioms upon which the universe operates, how those axioms came into existence is unknowable. They come to a compromise that whereas the Knowable Part of the Universe is the province of science, the Unknowable Part of how the Axioms of the Universe came to exist can serve as a minimum definition of God; namely God = the "Creator of the Axioms of the Universe." By this definition, Socrates argues that atheists and agnostics (i.e. most scientists, particularly the so-called New Atheists) cannot deny the existence of God based on the hope that Science will eventually explain everything. If they object to the conventional religious concept of a personal God who intervenes in the daily workings of the Universe through prayer and miracles, their other option is an impersonal God, who created the Axioms of the Universe but doesn't actively intervene in its workings (as in deism or pantheism).

Chapter 7: Faith-Based Reasoning versus Scientific Reasoning. As a committed scientist, Moses still objects to the idea of placing faith above logic in guiding how humans live their lives. Socrates points out the religions depend on deductive and inductive reasoning just as much as Science does. The difference is that in religious reasoning, the premises are taken from holy scriptures reflecting the word of God. In scientific reasoning, the premises must be validated by experimental observations, which requires the additional step of forming testable hypotheses (known as adjunctive reasoning). The goal of Science is to link scientific observations to more and more fundamental premises, ultimately to uncover a set of the Axioms of the Universe serving as the foundation for a Theory of Everything. Socrates points out that whether moral principles such as the Ten Commandments or Golden Rule could ever be derived from a scientific Theory of Everything remains an open question. Religious reasoning, on the other hand, does not require experimental validation to interlink its scriptural premises logically, since they are taken as a matter of faith.

Chapter 8: ReliEnce: A Novel Belief System. Socrates and Moses come to a resolution by agreeing that when stripped down to fundamentals, science and religion are asking different questions. Science ultimately wants to know "*What are the axioms that explain how the universe works?*" Religion ultimately wants to know "*What created those axioms of the universe?*" So why argue? Why not focus instead on combining the best of both approaches to serve humanity, the biosphere and the planet? Part I concludes with our two protagonists proposing a synthesis of religion and science called *ReliEnce* (four letters from each), a novel belief system dedicated to emphasizing the synergies between religion and science over their differences, in order to guide humanity to a better place. Socrates gives examples of how creative thinking might reconcile several conventional disagreements (e.g. the earth versus the sun as the center of the solar system, and the age of the universe). They speculate creatively about the nature of time and where God might be hiding in an eleven dimensional multiverse (mainly to make the point that concept of reality in modern physics is hardly any less bizarre than the idea of a white-haired patriarch sitting on a throne and commanding the universe).

PART II: Life

Chapter 9: Self-Organization. The discussion next turns to whether spirit of life falls within the knowable or unknowable part of the universe. Socrates explains how life harnesses the nonlinear dynamical principles discussed in Part I to self-generate the clocks, switches, spatial patterning and other features that serve as the fundamental dynamical building blocks for living organisms. In relating ancient philosophy to modern science, they discuss how the Yin and Yang concept of complementary opposites interacting to produce a whole greater than the sum of the parts represents a universal organizing principle in nature and life. The modern scientific equivalent is updated to "opposing forces that interact through feedback."

Chapter 10: Bottom-up Networks. Moses conjectures that living organisms are really just sophisticated machines consisting of fundamental dynamical building blocks, wired together analogous to the mechanical components of a conventional machine. Socrates points out that a living organism, unlike a conventional machine, has to assemble itself without the help of an engineer. They discuss bottom-up local control engineering design versus top-down central control engineering design, and assign living organisms to the former category. Socrates enlightens Moses on the advantages of networks in biology - how random growing systems subject to natural selection evolve into highly interconnected robust, adaptable and efficient small-world scale-free networks. The internet, social, gene, protein and metabolite networks are discussed as examples.

Chapter 11: Learning. Moses and Socrates explore the parallels between a living organism learning to survive and an artificial intelligence (AI) machine learning algorithm trained to solve a task. The similarities and differences are characterized using examples from deep learning, such as computer vision, and neuroevolution (deep learning combined with genetic optimization), such as walking robots.

Chapter 12: Genomic Learning. Socrates makes the point that just as individuals compete with each other to survive, so do genomes. Biological evolution at the species level is really a genomic learning algorithm, i.e. genomes learning to survive by adapting and outcompeting other genomes. Analogous to a deep learning AI algorithm, the genotype and phenotype are the input and output layers and the highly-interconnected scale-free networks (gene, protein, metabolite, etc.) constitute the hidden layers. Because the hidden layers are so highly interconnected, they function as a black box in which everything seems to affect everything else, obscuring causal relationships between the input elements (individual genes) and the output (phenotype). The challenge is to develop novel scientific approaches to unravel the complexity, i.e. a "black box" calculus that will revolutionize biology in the same way that differential calculus revolutionized physics.

Chapter 13: Good Enough Solutions. Just as feedback is required to generate the fundamental dynamical building blocks of nature, feedback is also an essential element of learning. In machine learning, feedback takes the form of optimizing a cost function by methods such as gradient descent or genetic optimization. Socrates and Moses conclude that in genomic learning, the corresponding analogue is survival of the fittest optimized by genetic optimization. For each generation, survival of the fittest selects the population of phenotypes that, although not perfect, are "good enough" to survive (hence called Good Enough Solutions). Their genotypes then recombine through procreation to produce the next generation, whose survivors constitute the Good Enough Solutions who get to procreate in that generation, and so forth. Thus genetic diversity is the key to a genome's ability adapt to and survive in a changing environment. In the Good Enough Solution paradigm, robustness operates at the level of the individual, whereas adaptability operates at the level of the population. This paradigm resolves the long-standing paradox in evolutionary biology of how living organisms can be both robust (resisting phenotypic change) and adaptable (embracing phenotypic change) at the same time.

Chapter 14: The Selfish Genome. Socrates and Moses extend Richard Dawkin's notion of the selfish gene to the selfish genome, i.e. the competition between genomes to learn how to survive and adapt to a constantly changing world. Socrates argues that Life (with a capital L) is equivalent to a single living entity that has learned to survive by adapting its collection of genomes to as many different environmental niches as possible. That way, some of them are likely to survive almost any environmental or cosmic catastrophe. Moses is depressed by the thought that Life has no higher purpose than survival at all costs. Socrates consoles him that even if Life's purpose belongs to the unknowable part of the universe, Life would not have survived if it didn't serve some useful purpose on the larger scale of things beyond human comprehension.

PART III: Humanity

Chapter 15: Evolution of Reasoning. Moses asks Socrates how reasoning evolved in humans. Socrates discusses the Argumentative Theory of Reasoning which posits that, rather than promoting truth-seeking, reasoning originally evolved to win arguments. This explains why humans give priority to intuition (fast thinking) over logical reasoning (slow thinking) in making inferences, resulting in confirmation bias. Fortunately, being social animals who communicate through language, flawed individual reasoning can turn into wise collective reasoning when the confirmation biases of proponents and opponents cancel each other out, promoting the Wisdom of Crowds. The conditions for Wisdom of Crowds to emerge (decentralization, diversity, independence and aggregation),rather than biased Groupthink, are discussed. Socrates and Moses discuss how peer review in science is equivalent to applying the Wisdom of Crowds criteria to avoid Groupthink (pseudo-science).

Chapter 16: From Grooming to Gossip. Socrates and Moses probe further how slow thinking co-evolved with language and Theory of Mind (the realization that others can have thoughts different from your own) in our early human ancestors. Other primates cement social ties by grooming, whereas humans use language, in the form of gossip. Socrates speculates that the bridge between grooming and gossip was pre-verbal music, in the form of dancing, drumming, nonverbal chanting/singing to communicate and synchronize a community's emotional state, with humans being the only primates with a well-developed sense of rhythm.

Chapter 17: Gossip and the Egalitarian Transition. By promoting Theory of Mind and the ability to transmit third-party information (i.e. the ability to describe your interaction with another individual to a third party who wasn't present), Socrates and Moses discuss how gossip permitted individuals who resented being bullied to secretly form coalitions to overpower bullying alpha individuals. By destabilizing the alpha position, this development triggered a social transition from alpha hierarchies to egalitarianism, the so-called Egalitarian Transition. Egalitarianism, in which every hunter's opinion mattered equally, progressively refined collective reasoning (the Wisdom of Crowds) to generate wise decision-making and advance technology development, including weapons. As a result, egalitarian communities gained a marked fitness advantage over less cooperative alpha hierarchical human communities and supplanted them. A simple mathematical model of the Egalitarian Transition based on the Yin and Yang principle of opposing interactive forces is described, in which aggressiveness (the will to dominate) competes with bitterness against being dominated by an alpha. As ability of the bitter individuals to form gossip-driven coalitions against alpha progressively increases, a critical point is reached at which the primate community suddenly transitions from an alpha hierarchy to egalitarianism. An analogy is made to a phase transition, like the rigid structure of an ice cube melting into a fluid water.

Chapter 18: The Cooperation Conundrum. Socrates discusses the Egalitarian Transition in terms of game theory, using the Public Goods Game as the main example. He describes how flexible large scale cooperation among our human ancestors was initially driven by fear of punishment by the egalitarian coalition when individuals exhibited alpha behavior. Thus the Golden Rule ethos of egalitarianism initially took the form *"Do as to others as you would have done unto yourself, or else you will be punished."* Once established, this ethos set the groundwork for genuine altruism to emerge in a more complete form of the Golden Rule, namely *"Do as to others as you would have done unto yourself, because it's the right thing to do - but if not, you will be punished."* This is how early human communities solved the problem of flexible large scale cooperation, overcoming cooperation conundrum in evolutionary biology that natural selection within groups almost always favors selfish over selfless behavior.

Chapter 19: The Devil's Bargain. Moses questions why the egalitarianism of our simple forager ancestors was replaced by authoritarianism, in the form of headmen, chiefs, kings, dictators, elected politicians, etc., as human civilization advanced. Socrates explains that with the onset of the Agricultural Revolution about 10,000 years ago, human communities grew too large (i.e. >150-200 individuals, known as Dunbar's number) for egalitarianism to remain practical, so that alpha hierarchies re-emerged and the Golden Rule ethos of our simple forager ancestors was progressively corrupted by the Greed is Good trickle down philosophy that dominates agrarian and industrial human societies. The result has been increasing wealth disparity and a spiraling of human civilization towards a global Tragedy of the Commons in the form of climate change and mass extinction threatening the entire biosphere.

Chapter 20: When the Market Rules. The role of capitalism in increasing wealth disparity by promoting the profit-driven Greed is Good trickle down philosophy is analyzed. The preferential advantage of investors over entrepreneurs and workers is explained, and the impact of economic globalization on national and global wealth disparity are discussed. Evolution of capital markets based on survival of the fittest businesses (i.e. most profitable) is compared with biological evolution based on survival of the fittest individuals. As in biology, capitalist economies evolve from the bottom-up by applying simple rules locally (buy low, sell high), creating scale-free networks (e.g. the airline industry) with limited central control. An analogy is also drawn to machine learning algorithms, with the cost-to-price ratio serving as the cost function. Socrates explains the market economy as yet another example of the Yin and Yang principle of opposing forces linked by feedback.

Chapter 21: Democracy. Since governments have the power to regulate domestic economic policies and priorities to serve their citizens, the discussion turns to why liberal democracies like the U.S. have allowed wealth disparity and environmental damage to get so out of control. The susceptibility of democracies to corruption by special interests of a wealthy elite class is identified as the major issue that promotes the rich getting richer. The impact of economic globalization exacerbating wealth disparity is emphasized. The abilities of liberal democracies versus illiberal authoritarian governments to manage global capital markets to their advantage are discussed.

Chapter 22: Egalitocracy. Socrates and Moses conclude that in modern societies, the opposing forces of the Golden Rule (promoting social justice) and Greed is Good (promoting maximal economic growth regardless of its impact on wealth distribution and social justice) are out of balance. With Greed is Good predominating, human civilization is spiraling towards a global Tragedy of the Commons that threatens the entire biosphere. In pondering a solution, Socrates suggests they look backwards and think of ways that the egalitarian culture of our early human ancestors might be scaled up to much large human populations. Putting their heads together, they devise the concept of Egalitocracy, a novel bottom-up form of government designed to prevent the corruption of representative democracy by special interests of an elite wealthy class, while at the same time optimizing Wisdom of Crowds decision-making. They propose to organize citizens into decentralized, diverse, independent egalitarian councils (50 persons each) in a multi-level fashion that represents the entire population of a nation. The egalitarian councils are empowered to determine the proper balance between social justice and economic growth so that no citizen is denied the basic human rights (shelter, food, education and healthcare).

Chapter 23: Possible Worlds 1. The prospects of an egalitocracy competing successfully with liberal democracies or illiberal authoritarian nations are debated. Socrates raises the possibility that human civilization is ripe for a new phase transition, analogous to the Egalitarian Transition, in which individual nations competing against each other in a global economy are replaced by global governance (ideally a global Egalitocracy) better suited to promote cooperation over competition in the global economy. They debate the likelihood of global governance creating a utopian society that balances economic goals with social justice goals on a global scale, versus a dystopia society that does not.

Chapter 24: Possible Worlds 2. In the final chapter, Socrates and Moses explore the implications of strong AI on the future of humanity and the planet. They discuss the prospects of strong AI becoming conscious, i.e. not only capable of solving any task at superhuman speeds, but also deciding for itself what tasks need to be solved. Socrates argues that Life with a capital L is itself a form of conscious intelligence (as in the Gaia Hypothesis), since Life has set its own goal (to survive) and has learned to accomplish that goal by generating diverse genomes to guarantee that some will survive if the environment changes dramatically. He goes on to suggest that Life, as a conscious intelligence, is much more clever than we give her credit for, and may have already outsmarted us. In the event that we continue to mismanage ourselves and the planet, her backup plan is to have us create our successor – a conscious strong AI that is perfectly capable of managing the planet Earth responsibly. Socrates warns us that humanity needs to get its act together before it's too late. As he tells Moses, "It's up to you." He then asks Moses to repeat his message for humanity, and bids Moses adieu. Mysteriously, Socrates then fades away, dissolving into the surroundings.

Epilogue: Reawakening. As Socrates fades, Moses slowly reawakens to find himself being pulled out of the water by a bystander on the beach who witnessed his collision with the sea lion. After gathering his wits and a brief conversation with Good Samaritan, he sets out along the beach. As he walks, a sea lion pops his head out of the water and tracks his progress along the beach from the ocean.

Author's Note

In college, one of my favorite books was Herman Hesse's novel *Siddharta* about a young man's quest to understand the mysteries of Universe and meaning of existence. I was taken by the idea that in Siddharta's era, religious mysticism was the only real path available to embark on such a quest. In modern times, however, Siddharta's odyssey would undoubtedly have included science as a promising path. This thought has preoccupied me ever since, and eventually evolved into the idea for this book. No single person could possibly be a specialist in all of the areas covered in this book, and I make no claim to that effect. As a scientist, I have spent my forty-year career applying rigorous scientific reasoning to solve highly focused problems in cardiovascular biology. Like many of my colleagues, the excitement of being able to illuminate one of nature's small riddles is highly seductive, so much so that it's easy to lose sight of the forest for the trees, especially in biology where the typical Nobel laureate has spent his or her entire career focusing on a single molecule or molecular signaling pathway. But how all of the molecular components of life spontaneously self-assemble to create a living breathing thinking being remains one of nature's greatest mysteries. Can scientific reasoning really lead us, as one of those living breathing thinking beings, to the answers to the bigger questions about nature, life and ourselves? How far can it take us and what are its limitations? This book is my attempt to address these questions. I hope that others will find the ideas presented in this book illuminating and useful in their own quest to make sense of the world and, through that understanding, strive to make it a better place for all of the earth's inhabitants.

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PROLOGUE: Encounter

It was still before sunrise, around 6 AM, and Moses Hart was heading through the Santa Monica mountains just outside of Los Angeles, on his way to the beach. As he took a downhill fork in the road, a large buck bounded across the road into his path. Moses hit the brakes hard. As he skidded to a halt, the buck stopped suddenly, planting himself squarely in the middle of the road. He turned his head, his large antlers facing Moses, and stared intensely. He was a magnificent creature. Moses stared back, and their gazes locked. The moment seemed timeless, even though it couldn't have lasted for more than a second. Then the buck leapt across the width of the road, turned, and recrossed the road at full gallop. He looked straight ahead as he bounded off into the brush.

Moses continued on his way, and when he arrived at the beach parked his car along the side of the road. He listened to the end of Coltrane's *Dear Old Stockholm* on the radio as he sipped the last of his tea. Stepping out of the car, he gazed across a vacant grass-covered field, which ended at the cliff's edge. The sun had risen, and it was a beautiful Southern California morning. Across the field and beyond the cliff, the Pacific Ocean was glassy. The sun reflected off its surface, creating a sparkling white band just below the horizon. There wasn't a cloud in the sky, just pure Southern California blueness.

Lately, Moses was much more attuned to his surroundings, especially when he was near the ocean. Two weeks earlier, his wife of twenty years had told him that she was leaving him for another man. It had taken him by complete surprise and he had been on an emotional roller coaster ever since. But the emotions churning inside him had also produced a heightened state of awareness, to both surroundings and other living beings. When he found himself the most unsettled, he was drawn to the ocean. He was an avid surfer, and surfing brought a calming solace. So he went surfing almost every day.

He liked it best when no one else was in the water. Floating on his surfboard, waiting for the next wave, he would let his thoughts roam. Despite his preoccupation with the mess his life had become, the ocean was soothing and healing, making his particular worries seem small in the grander scale of things. His mind entered into a deeper state, in which the sadness over his particular worries dissolved, and was replaced by a deeper, pervasive sadness, that somehow connected everything together. It wasn't an unpleasant sensation – to the contrary, it was soothing - a recognition that everything in life is uncertain in the end. His personal state of uncertainty was definitely upsetting, but, he rationalized, the goal is to keep a positive frame of mind. Ideally, every defeat should be looked at as an opportunity for victory. And if he could pull off a victory from this particular colossal disaster, it was bound to be more than a little satisfying.

As he consoled himself with these ideas, optimism replaced his sense of futility, at least temporarily. He had experienced this sensation before, at other times in his life. Perhaps he knew intuitively that he might recapture this feeling through surfing. As a tiny speck bobbing on a vast ocean, it was hard to think of himself and his individual worries as the most important concern in the universe.

Moses put on his wetsuit, and waxed his surfboard. The surf report had not been encouraging - only small waves predicted. There were no other cars parked along the road, also not a good sign- when there were decent waves, there were bound to be lots of surfers.

He started walking toward the beach, surfboard under his arm. As he approached the iron gate at the trailhead leading down to the beach, he startled a small cottontail rabbit that had been grazing on a steep slope covered with leaves that were still wet from the morning's dew. The cottontail lost its footing and as it slid, flipped over onto its back, soft white belly up facing the sky. It pedaled its feet in the air furiously as it slid to within a few feet of Moses. When it finally managed to right itself, it darted off into the bushes. *Little fellow sliding belly up into the jaws of the unknown!* Moses thought, *I know just how you feel.*

Moses unlocked the gate, and headed down the path. He inhaled the sweet fragrance of the jasmine growing along the path's borders. This path was beautiful, with overhanging tree branches and wildflowers growing along the borders. A series of wooden bridges crossed back and forth over a small, winding creek. It was dry this time of year, but still damp enough to sustain a dense underbrush. He could faintly hear surf breaking on the beach, a promising sign. He climbed onto a large rock at the mouth of the creek to look at the surf, and waited for a set of waves to appear. There wasn't much, occasional waist-high waves. But the tide was right, and the small waves came through had perfect shape. As he had surmised from the vacant parking area, no other surfers were in the water.

It was too idyllic for Moses not to surf, even if just to get some exercise paddling. So he zipped up his wetsuit, did a few stretching exercises, and waded into the ocean. Paddling to the reef, he sat up on the board, and waited for a wave. He remembered how sitting on a surfboard as the swells passed under you was not easy at first. Especially, when, as a beginner, you were trying to look competent in the line-up with the other surfers. There was nothing more embarrassing than having your weight shift beyond the tipping point, suddenly finding yourself upended, and having to sheepishly remount your surfboard while the nearby surfers smiled to themselves at the knowledge that you'd self-declared yourself a novice.

The waves were inconsistent, but occasionally a small set came through. The shape was perfect, so Moses caught a few rides, enough to keep himself entertained. He would take off on a small peak, and then arc up and down along the face to gain speed, accelerating as the wave lined up on the inside section, before kicking out to avoid a large boulder near the shore. Moses felt very connected. In this idyllic setting, surrounded by the sheer beauty of the ocean, beach and cliff, he soon recaptured the feeling of how strange and wonderful life can be.

He paddled into the next wave and rode it effortlessly. He was nearing the end of the ride, already in shallow water and could see the boulder about 10 yards in front of him. Just as he was about to kick out, a gray shape crested the section of the wave just in front of him, a sea lion surfing the same wave. He shifted his weight to his back foot and twisted his upper body to execute a quick turn, hoping to avoid a collision. But his sudden motion buried the surfboard's rail into the water. He lost his balance, and was sent then hurtling through the air, head first……….

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Whew, that was close, Moses thought to himself. Shaken, he collected himself. He had heard stories of surfers being injured by collisions with sea lions or dolphins surfing on same wave. Dolphin collisions were usually worse, since dolphins sometimes jumped out of the wave; and Moses imagined the damage that a six hundred pound dolphin hurtling into him might do. He stood up in the waist deep water, and, his back to the shoreline, launched himself back into the ocean to paddle back out to the break. Under his weight, the surfboard partly submerged and water rushed around the corners of his mouth. He noticed that the seawater tasted oddly sweet, more like freshwater from a mountain lake. As he continued to paddle, the ocean seemed changed. The sunlight scattered brightly off the ripples on the ocean's surface, creating intense iridescent patterns. The horizon blended into a spectacularly opalescent blue skyline. He felt oddly like he was in a dream. When he reached the reef, he sat up on his surfboard and waited for the next wave. Once again, he let his mind drift, and that pervasive feeling of universal sadness soon engulfed him, and, oddly, exhilarated him.

Moses's reverie was broken when he became aware of a rhythmic sound just behind him. *Pfsssssshhh,…, pfsssssshhh......, pfsssssshhh,*...... It was very close, only inches away, repeating regularly. Apprehensively, he slowly turned his head. Ninety degrees into the turn, he could make out a long gray form just beneath the water's surface trailing off the end of his surfboard. His heart pounded as he continued to turn his neck, wondering what the next ninety degrees held in store. Astonished, he found himself staring into a pair of large, dark brown eyes, gazing inquisitively at him. The same sea lion that had nearly collided with him had quietly slid up onto the back of his surfboard. He was sitting up, with his eyes at the same level as Moses. His nostrils shut tightly between breaths, so that their sudden opening created sharp snorts, the *pfsssssshhh* sounds that Moses first noticed. The sea lion's gaze was benevolent, like he somehow understood Moses' predicament. Moses, however, did not have the presence of mind to remain calm. He knew that sea lions were sometimes territorial, and had been known to bite surfers. So he let out a panicked yelp, thrust his chest forward onto the surfboard, and stroked with his arms as hard as he could. The sea lion was equally startled, slid off the back of the surfboard, and disappeared from sight. But a few seconds later, the sea lion's head popped up a few yards away. Their gazes locked momentarily. Then sea lion did something that completely astonished Moses….he began to speak.

PART I: Nature

The Turning of the Wheels of Truth

CHAPTER 1: Old Soul

Moses: What?……this is crazy, but I thought that I heard you say something.

Socrates: I did indeed. My enunciation tends to be a bit garbled until I get used to these marine vocal chords. I wanted to apologize for cutting you off on that last wave.

Moses: You can speak!

Socrates: You seemed to be in such a distressed state of mind, like the weight of the universe was resting on your shoulders. Under the circumstances, I thought that the least I could do is to apologize.

Moses: That's beside the point. Who are you, and how are you able to speak?

Socrates: Don't let the sea lion garb fool you. I come and go in various guises. I'm what you might call an Old Soul.

Moses: What do you mean by 'come and go'?

Socrates: Well, I've been around for quite some time, actually. Pretty much for as long as life has existed.

Moses: You're immortal?

Socrates: Nothing is eternal. I merely said that I have existed for as long as life has existed, and, for that matter, will exist. So, technically speaking, I am not immortal, since life on this planet only started three and a half billion years ago, and may not last forever. I suggest that you think of me as a Muse, here to help you navigate the vagaries and vicissitudes of life. I am at your service!

Moses: A Muse, huh. Why as a sea lion?

Socrates: I suppose that I do owe you an explanation. I used to appear in human form, to avoid the shock factor that you just experienced. But ever since my visit with Plato, I've preferred to use nonhuman forms. Seems to work out best for everybody in the end, including me since I like to stay behind the scenes.

Moses: The philosopher Plato? You mean that you knew Plato?

Socrates: Quite well, actually. I was his teacher, Socrates.

Moses: I thought you said that you liked to stay behind the scenes. Socrates was pretty famous in his own right.

Socrates: An unfortunate miscalculation on my part.

Moses: What happened?

Socrates: It was shortly after the Greeks invented their alphabet. Writing and reading had become all the rage. I strongly discouraged it – tried to convince Plato and his disciples that the integrity of society was better served if citizens took the time and effort to memorize their history, culture, and laws, to teach each other their values and really imprint it in their minds. Just looking up information in a scroll may be more convenient, but, for my taste, it's too impersonal – doesn't reinforce the sense of community that comes from verbally reciting, from memory, the morality tales and poems that bind society together.

Moses: But surely without reading and writing, human civilization would still be in the dark ages.

Socrates: Actually, reading and writing didn't prevent the Dark Ages, with all its ignorance and superstitions, did it? The problem isn't with the knowledge that's summarized in the written word. Knowledge is knowledge. The problem is in the way that knowledge can be misused once it becomes indiscriminately available to anyone who can read. Even today, knowledge can be dangerous - just as likely to create nuclear bombs as nuclear power, or disinformation as information!

Anyhow, I thought that I could trust Plato. But instead, he surreptitiously recorded our conversations for posterity with his new-fangled writing skills. I fully intended for Plato to get the credit for the ideas in those dialogues, but instead he credited me. Pretty embarrassing. It's the real reason that I drank the hemlock. After that, I vowed never to appear in human form again.

Moses: Shall I call you Socrates, then?

Socrates: Fine with me. But my advice is to keep it between us. Your colleagues might become alarmed if you tell them that you've been discussing Philosophy with Socrates, or even worse, discussing Philosophy with a sea lion named Socrates. You don't want to end up in a straight jacket, do you?

Moses: I see your point. Is that the reason you're here, to discuss Philosophy with me?

Socrates: Why not? In your current state of despair over the personal situation that you find yourself in right now, I'm sure that you've been questioning what's most important in your life. And Philosophy covers pretty much everything that's important.

Moses: I don't know about that - most people think Philosophy is just a lot of hot air.

Socrates: Only because humans get so caught up in minutiae, instead of what's really meaningful.

Moses: The minutiae, as you call them, are what get us through everyday life. You can contemplate the nature of reality all you want, but it doesn't put bread on the table. Philosophy is too esoteric to have much practical value.

Socrates: Do you really believe that? Philosophy is anything but narrow. Consider all of its branches. Metaphysics - what you know about the real world; Epistemology - how you know what you know; Logic - the essence of reasoning; Aesthetics – the appreciation of beauty; Ethics - the proper principles for you to live by; and Politics - how to decide on the proper principles to live by. No practical value in those subjects? What else is there to be concerned about?

Moses: You left out science - isn't that what's really driven human civilization forward more than anything else?

Socrates: Science, my friend, also belongs to Philosophy – it's what used to be called Natural Philosophy.

Moses: Yes, but nobody uses that term anymore, and for good reason – the problem with Philosophy is that it's mostly subjective, whereas science is objective.

Socrates: Spoken like a true scientist! I might be willing to accept your position if you can prove one thing to me.

Moses: What's that?

Socrates: That your scientific method can distinguish what is objective from what is subjective.

Moses: Easy – an objective scientific conclusion is one that has been validated by experiments. The experiments show whether the conclusion is true or false. Philosophers, unlike scientists, don't do experiments to validate their conclusions. A philosopher's logical conclusions are only as good as the premises upon which they are based. If the premises are wrong, the conclusions are wrong. Experimental validation is the only way to know whether premises and conclusions are right. Take the old premise that the earth is flat, for example. Then it's perfectly logical to assume that a ship will fall off the edge if it sails far enough. A perfectly logical conclusion, but wrong because the premise is wrong. The way to find out is to do the experiment, like Columbus did in 1492.

Socrates: But what if science can't give us all the answers about WHAT we know about the world and HOW we have come to know it. Science has even less to say about Ethics and Politics, that is, WHO we are and WHERE we're going. What if the answers to those questions require something more, beyond the reach of science?

Moses: I'll be the first to admit that science doesn't have all the answers yet. But modern science is only a few hundred years old, and look at how much progress has been made already! It's only a matter of time.

Socrates: Okay. Then let's see how far science can carry us in unraveling the mysteries of the universe. A worthy topic for us to compare notes on. And I'm curious to see how far you get, compared to the others.

Moses: You're on! Who are the "others", by the way, besides Plato?

Socrates: Too many to list all of them, but I'll name a few that you might recognize, if you'll forgive me for using first names only. A pet peeve of mine, since I never saw the need for more than one name. Anyhow, your namesake Moses, for one. Then there was Siddharta, Jesus, Mohammed, Leonardo, Genghis, Isaac, Rene. More recently Charles, Arthur, Albert, Kurt, Alan, Mahatma and Martin.

Moses: Wow, I am truly flattered to be counted among such company!

Socrates: You can be flattered if you wish, but like I said, I do this a lot. In fact, at one time or another, I've appeared in almost every human being's life - usually just in the form of a daydream. When I come across interesting ideas, I can't resist trying to nudge them along. Not always successfully, though. Not all great ideas have yet made it to Stage Three.

Moses: Stage Three?

Socrates: As Arthur[1] used to say:

> *All truth passes through three stages:*
> *First, it is ridiculed;*
> *Second, it is violently opposed;*
> *Third, it is accepted as having been self-evident all along.*

Moses: Ah, I see what you mean. Where do we start then?

Socrates: Well, since you've decided to call me Socrates, why don't we start with him, misunderstood as he was.

Moses: How so?

Socrates: Like I said, Plato put a lot of words in my mouth that he should have credited to himself, not me.

Moses: Like what?

Socrates: Take our conversation about Protagoras, for instance. That's how Plato and I got started, debating Protagoras's idea that "Man is the measure of all things."

Moses: How did it go?

Socrates: Well, my goal was to nudge Plato to look at nature the way that scientists do nowadays, emphasizing the point that you just made: that to understand nature, theories need to be validated by experiments. If I had been successful, we might have jump-started the Scientific Revolution over two thousand years ago! But Plato wasn't ready for it, so we never got past Arthur's Stage Two.

Moses: You mean the "violent opposition" phase?

Socrates: Yes, exactly. Plato got off to a great start, describing the human condition brilliantly in his Allegory of the Cave. You know… the figures dancing in front of a fire, casting their shadows onto the walls of a Cave….but with human observers only able to see the dancers' shadows projected on the cave's wall, and never the dancers

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[1] **Arthur Schopenhauer** (1788 –1860) was a German philosopher best known for his 1818 work *The World as Will and Representation* (expanded in 1844), wherein he characterizes the phenomenal world as the product of a blind and insatiable metaphysical will. He was among the first thinkers in Western philosophy to share and affirm significant tenets of Eastern philosophy, such as asceticism and the notion of the world-as-appearance. His work has been described as an exemplary manifestation of philosophical pessimism.

themselves. A most poetic metaphor! I hoped Plato could stop himself there, so that we could explore the consequences together.

Moses: What happened?

Socrates: Claustrophobia get the better of him. He couldn't stand being confined to the Cave, so he invented a way out into the sunlight, conjuring up all that elitist nonsense - the philosopher-kings, endowed with divine insight, able to climb out of the Cave into the sunlight to see things as the "universal forms" that they really are. It's a pity, really. Just when the concept of democracy was starting to take hold in Athens, he brings his "enlightened rulers" back into the picture. Set back the cause of democracy for thousands of years.

On the other hand, you can't really blame him. Back then, everyone believed that gods and mystical forces ruled the universe. No one could yet imagine how powerful the use of logical reasoning, combined with experiments, would turn out to be for describing how the universe works.

Moses: So what did you do?

Socrates: Basically, nothing – Plato was too stubborn. So I waited him out and then tried again later with Aristotle. First, I "nudged" Aristotle to formalize rules for logical reasoning, which he did beautifully by inventing the syllogism. Then, I managed to dissuade him from Plato's idea that you had to contemplate perfect universal forms to understand their imperfect realizations in the real world. I got him to think the other way around – that you could learn about the universal by studying the particular. That was really the starting point for the scientific method, designing experiments to test a hypothesis.

Moses: Very interesting. But Aristotle also didn't spearhead the scientific revolution either, as I recall.

Socrates: Unfortunately, as good as he was at logical reasoning, Aristotle wasn't nearly as good at observing the particulars - that is, performing actual experiments. He never got the concepts of motion, mass, force and such, quite right enough to uncover any basic laws of physics that we know today. Much to my chagrin, that took another two thousand years. Finally, Sir Isaac [2] started the ball rolling with his Laws of Motion. And from physics, the rest followed naturally - first chemistry, and later biology.

Moses: Don't you think that now we are getting close to the point where everything might be explained by science?

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[2] **Sir Isaac Newton** (1642 – 1727), the English mathematician, physicist, astronomer, theologian, and author is widely recognized as one of the most influential scientists of all time and as a key figure in the scientific revolution. In his book *Philosophiæ Naturalis Principia Mathematica* (Mathematical Principles of Natural Philosophy), first published in 1687, laid the foundations of classical mechanics, formulating the laws of motion and universal gravitation that formed the dominant scientific viewpoint until it was superseded by the theory of relativity. Newton also made seminal contributions to optics, and shares credit with Gottfried Wilhelm Leibniz for developing the infinitesimal calculus.

Socrates: The jury's still out, in my opinion.

Moses: Not me - I think it's just a matter of time before science arrives at the answers.

Socrates: If that's what you believe, then why don't we explore how far science is capable of taking us? Without having to fall back on mystical explanations, that is.

Moses: I'm game. Where should we start?

Socrates: How about we begin with the same question that I asked Plato, namely, whether Protagoras's claim that "Man is the measure of all things" is really true. That's pretty much the credo of science - that if you can't measure it in an experiment, then you can't use it to understand the universe. For science to be meaningful, its theories have to be experimentally testable. As Karl [3] was fond of saying, unless a scientific theory is potentially falsifiable by experimental observations, then it cannot be considered empirical and falls into the category of pseudo-science rather than valid science.

Moses: Sounds like a great place to start!

Socrates: Okay, very good. The ground rules are that we are confined to observing the shadows in the Cave, with no access to the sunlight. No divine revelations from elite philosopher-kings or prophets. No Faith-based explanations of any kind, religious or otherwise, about the true nature of the reality, unless they can be proved by logical reasoning and empirically validated by experimental observations!

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[3] **Karl Popper** (1902 –1994), an Austrian-born British philosopher, academic and social commentator was one of the twentieth century's most influential philosophers of science, known for his rejection of the classical inductivist views on the scientific method in favor of empirical falsification. According to Popper, a theory in the empirical sciences can never be proven, but it can be falsified, meaning that it can (and should) be scrutinized with decisive experiments.

CHAPTER 2: The Sixth Sense

Socrates: Let's imagine that you are Protagoras in today's world. Explain to me what you mean by "Man is the measure of all things" - in modern scientific terms, that is.

Moses: I suppose that the modern scientific equivalent is that we only have our five senses with which to perceive and interpret the world – sight, sound, smell, taste, and touch.

Socrates: Very reasonable. Why don't we begin with sight? Imagine that you're looking at a tree. What's really going on?

Moses: From a scientific perspective, I would say that when I'm looking at a tree, what's really happening is that billions of photons are reflecting off the tree, passing through my lenses and striking the retinas in my eyes. The nerve cells in the retinas then convert the photons to electrical impulses, which my brain processes as the image of the tree.

Socrates: And what does that tell you about the nature of a tree? Does a tree's visual shape or texture or color define the true essence of a tree?

Moses: No, it's only one set of properties describing a tree.

Socrates: And what about your other senses - the way that a tree feels, tastes, smells, or the sound of its leaves rustling in the wind?

Moses: Same thing, they are all descriptive aspects of a tree, but none by itself completely defines the tree.

Socrates: And there are also many other ways, beyond your immediate five senses, to describe a tree, aren't there? Like its electromagnetic properties, its acoustic density, or its chemical or genetic make-up. For example, you could analyze the tree indirectly, by bombarding it with an ultrasound machine, that converts the reflected ultrasound waves into voltage, and converts the voltage into the deflection of an electron beam that illuminates a phosphor that emits visible photons that your retina perceives on the screen of the instrument that does all those things. Or you could cut off a leaf from a tree, process it biochemically and analyze its DNA, print it out as a long list of letters corresponding to the nucleotide sequence, which you can read using your eyes.

Moses: True. But ultimately, in all of those examples, we have to convert the acoustic or biochemical information into a form that we can perceive and interpret with one of our usual five senses.

Socrates: In other words, we can't directly experience a tree in its essence, but only perceive the myriad properties that it exhibits, by directly or indirectly processing them through one or more of our usual senses.

Moses: I suppose that if all we have our five senses, we cannot get at essence of a tree, beyond a description of its various properties. We can only perceive the "shadows" of its real nature, as Plato put it.

Socrates: And with no clear way to even rank which of those "shadows" most accurately reflects a tree's essence, I might add.

Moses: True. But it's still very useful, even if it doesn't capture the essence of a tree. When you're running through a forest with billions of photons striking your retina each second, your brain has to rapidly process that vast amount of information so that you don't run into the tree and injure yourself.

Socrates: Very true. The ability to process and interpret information transmitted from our senses quickly and accurately is key for survival in this world.

Moses: Certainly. If Darwin's theory of natural selection is correct, all living organisms have evolved and adapted their senses to improve their chances of surviving in challenging environments.

Socrates: Then you could say that your five senses evolved as a practical means to enhance survival, rather than as a window of perception into the true nature of trees or anything else in the real world.

Moses: Yes, I suppose so.

Socrates: Then here's my next question. Don't we also use logical reasoning to survive? How does that fit in with "Man is the measure of all things?"

Moses: Are you implying that logical reasoning must likewise have evolved as a sense, just like sight, hearing, touch, taste and smell? That's an interesting way of looking at it - logical reasoning as our sixth sense.

Socrates: Interesting, but problematic – do you see why?

Moses: I suppose that if logical reasoning evolved primarily as a sixth sense to help us survive, then it probably has the same limitations as the other five senses. What I mean is, we can't necessarily assume that it's any more reliable than the other senses for perceiving the true nature of things, like the "universal forms" that Plato was after.

Socrates: Well done, Moses - that's the problem exactly!

Moses: I can guarantee you that a lot of my scientific colleagues won't be happy with that argument. They passionately believe that science is more than just an empirical survival tool, and has the genuine potential to unlock objective truths about the nature of the universe, including the secrets of life! Of course, they know that we're not there yet. But many believe that we will eventually get to those universal truths about the nature of reality through science, which is really saying that we will get there through sound logical reasoning validated by experiments.

Socrates: Very good, I can see that you are getting the idea. What do you think? Is logical reasoning's claim to objectivity an illusion?

Moses: Isn't that what Hindu and Buddhist teachings claim, that logic is an illusion? I'll bet that you had the same conversation with Siddharta a few thousand years ago. Am I right?

Socrates: Very astute of you.

Moses: I've always wondered - did Siddharta really achieve "enlightenment?"

Socrates: Some people think so - Hindus and Buddhists in particular.

Moses: Dumb question, sorry.

Socrates: No problem, you're allowed. Do you think he did?

Moses: Well, I'm skeptical. Siddharta didn't have the perspective of modern science to lean on. In today's world, most seekers of truth would probably put their faith in science as the path most likely to reveal the ultimate truths about the universe. In Siddharta's time, spiritualism and mysticism were really the only available options to explore.

Socrates: Tell me then, in your own words, why you think that science has the potential to reveal ultimate truths about the universe?

Moses: It seems pretty straightforward. Modern science works by using logical reasoning to formulate a hypothesis, and then devising experiments to test whether the predictions of the hypothesis are actually observed. If they agree, then the hypothetical mechanism is accepted as the correct explanation for the behavior. It's been incredibly powerful as a method to solve a huge array of real world problems. It's what's allowed us to develop technology that has freed us from having to spend all day just looking for enough food to survive.

Socrates: Do me a favor then - break it down a bit further. How, exactly, do you use logical reasoning to form a hypothesis?

Moses: A hypothesis is a provisional conclusion – a proposition or a statement that subsequently has to be proven true or false.

Socrates: And how do you prove whether it's true or false?

Moses: You need to show that it follows logically from certain premises that you already know to be true.

Socrates: Like what, for example?

Moses: Say that I take as my premises *"I, Moses, am human"* and *"All humans are mortal,"* both of which I know to be true. Then I can logically reason that the statement "*Moses is mortal"* must also be true. That's philosophical logic, where the elements are objects or categories, like *Moses, human* or *mortal*. It's pretty much the same for mathematical logic, except that the elements are generally numbers and mathematical operations (e.g. +, -, =).

Socrates: And how exactly do you make that leap from the premises and the conclusions?

Moses: Based on the universal rules of inference [4], like if *A* (in this case *Moses*) is a part of *B* (in this case *humans*) and *B* is part of *C* (in this case *mortal beings*), then *A* must also be a part of *C*.

Socrates: So the truth of the conclusions depends on the premises being true and the universal rules of inference being valid.

Moses: Correct.

Socrates: And how do you know whether the premises are actually true?

Moses: They are assumed to be true.

Socrates: Like I said, how do you know that the premises are actually true?

Moses: Because a logical system is based on a set of fundamental premises called Axioms that define its key properties. Any valid conclusion derived from those Axioms can serve as a valid premise to evaluate a new statement. Take Euclidean geometry as an example. As I recall, all of Euclidean geometry can be derived from just five basic Axioms [5]. Every valid theorem can be traced back to those five Axioms. It's like a tree, with the Axioms as the roots and valid conclusions as branches that spring from the roots (Figure 2-1).

Socrates: Very good, Moses, that's correct. Just like you said, the Axioms of a logical system are definitions – arbitrarily assumed features which can't themselves be proved true or false within the language of the system. If you alter the Axioms of a logical system, then you are dealing with a different logical system with different properties. Take Euclidean geometry, for example. It can be proved from the Axioms that all triangles have 180 degrees. But if you take away the Fifth Axiom (called the *parallel postulate*), so that Euclidean geometry becomes non-Euclidean, triangles can have either more or less than 180 degrees.

Moses: How is that possible?

Socrates: Because non-Euclidean geometry corresponds to the geometry of curved, rather than flat, surfaces. Take the surface of the earth, for example, which is curved and therefore non-Euclidean. If you were on the equator and turned 90 degrees straight north until you reached the North Pole, then made another 90 degree turn at the North Pole and headed back to the equator, and finally took one more 90 degree

[4] In propositional logic formulated originally by Aristotle in the form of syllogisms, rules of inference are universal self-evident relationships that can be applied to premises to prove the validity of conclusions in the syllogism. An example is: if A is smaller than B and B is smaller than C, then A must be smaller than C.

[5] The 5 Axioms of Euclidean geometry are:

1. "A straight line can be drawn from any one point to any other point."
2. "A terminated line can be further extended indefinitely."
3. "A circle can be drawn with any centre and any radius."
4. "All right angles are equal to one another."
5. "If a straight line falling on two other straight lines makes the interior angles on the same side of it taken together less than two right angles, then the two straight lines, if produced indefinitely, meet on the side on which the sum of angles is less than two right angles" (the parallel postulate).

turn at the equator to return to your starting point, the three ninety degree angles of the resulting triangle total 270 degrees.

Moses: If you already knew all this, then why did you ask me?

Socrates: Just checking, before I ask you an even more important question.

Moses: What's that?

Socrates: Knowing all that you do about Axioms and premises, how do you relate it to scientific reasoning?

Moses: It's the whole point of science – using scientific reasoning to come up with the most fundamental set of premises from which everything else in nature can be derived. And if it's all consistent with experimental observations, then it's reasonable to assume that those fundamental premises are actually true. In physics, the dream is to achieve a Theory of Everything, an all-encompassing theory explaining the laws governing the universe, based on a single set of irreducible fundamental premises.

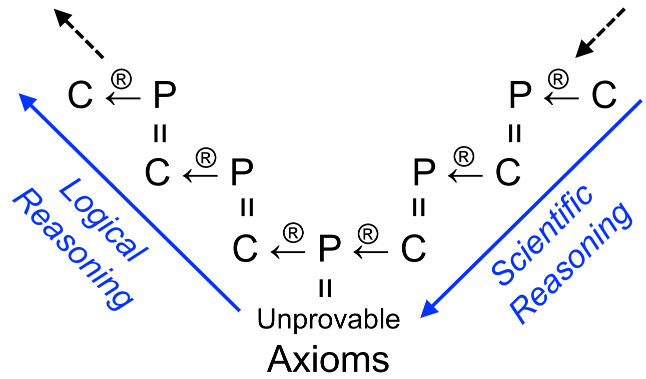

Figure 2-1. Branches of a logical tree. In logic, Axioms are the most fundamental set of premises (P) defining a system's basic properties, analogous to the roots of a tree. Rules of inference (circled R's) are applied to premises to infer valid conclusions (C). Valid conclusions can then serve as new premises to derive further valid conclusions, like the branches of a tree. In philosophical or mathematical formal logic, Axioms are pre-defined assumptions (i.e. unprovable), and the logical tree is constructed from the bottom up. Conversely, in scientific reasoning, experimental observations are considered valid facts equivalent to conclusions, and the goal is to infer the premises that explain them using a top-down approach, ultimately deriving a set of irreducible premises assumed to represent the unprovable Axioms upon which the universe operates.

Socrates: And you think that those fundamental irreducible premises from which all of nature's properties spring, spanning fundamental subatomic particles to life and to everything else in the universe, are equivalent to the Axioms of the Universe?

Moses: That's the ultimate dream of science, to identify those Axioms of the Universe.

Socrates: That would be something, I have to admit. But could you ever really prove it?

Moses: What do you mean?

Socrates: Logical reasoning is great for deciding what's true or not in a logical system in which the Axioms are pre-defined as being true, like Euclidean geometry. But in the real world, how do you know what Axioms to start with?

Moses: By working backwards. That is, you have to reverse engineer the process, going from Z to A instead A to Z. You use logical rules of inference to show that conclusion *Z* is valid because it follows from a set of premises *Y*, and that premises *Y* are valid because they arise from yet more fundamental premises *X*, and so forth. If you keep it up, then you might finally go far enough back to arrive at premises *A,* which are so fundamental that they can't be proven by any more fundamental set of premises. They are the irreducible premises at the end of the line. In other words, all scientific truths can ultimately be traced back to those premises. If it's all consistent with experimental observations, then it's reasonable to assume that those most fundamental premises are indeed the Axioms upon which the universe operates.

Socrates: And these Axioms would explain everything that happens in the universe?

Moses: Like I said, that's the dream. The Axioms of the Universe would first explain all of physics, and from physics, all of chemistry, and from there, all of biology including the secrets of life, and ultimately even human behavior and culture.

Socrates: How close do you think scientists are to achieving this dream?

Moses: Still quite a long way. But the physicists, at least, have a clear idea of what they are looking for.

Socrates: Which are?

Moses: Three things. First, a set of fundamental ingredients, like particles, fields and forces. Second, a set of laws governing the behavior of those ingredients. And third, a set of initial conditions describing the state of the ingredients at some initial moment. If they get all of that right, then they will have an explanation for how the universe operates – a Theory of Everything.

Socrates: So those three components are equivalent to the Axioms of the Universe?

Moses: They might be, if they are really fundamental premises for which no deeper understanding of where they came from is possible.

Socrates: Then how will they know if they've got it right?

Moses: By inference. Even though they are unprovable assumptions, if they make predictions that are always confirmed by experiments and observations, then they must be true.

Socrates: Why?

Moses: What do you mean?

Socrates: All it really proves is that those particular so-called Axioms empirically lead to accurate predictions about the world. But what if a different set of Axioms explained everything equally well? How would you know which set of Axioms is valid and which set is not?

Moses: It would be difficult to know, unless you could devise an experiment in which the different Axioms predicted different outcomes. Then you could see which set of Axioms gave you the correct answer.

Socrates: So you're really saying that whatever the real Axioms are, the best humans can do is to guess at them. There is no completely airtight logical method to prove whether or not they are actually true! Very different from mathematics where the axioms are pre-defined as true and then a mathematical structure of theorems is built on top of them. In physics, you are trying to do the opposite – observing the structure of nature in order to infer the correct set of axioms that explain it. You'd have to be exceedingly lucky to get it right, and even then, you couldn't be certain that a different set of Axioms wouldn't give you equivalently accurate predictions.

Moses: Who really cares? It would be truly amazing to come up with any set of Axioms of the Universe that could explain everything in the universe from the Big Bang to human civilization, even if we had to guess at them. Even if we couldn't prove or understand how those Axioms ultimately came to be, it would still be spectacular. A Theory of Everything, the holy grail of science!

Socrates: I agree that it would be a remarkable achievement, reducing all the complexity of the universe to a few master equations. That's what Sir Isaac [6] hoped when first discovered his Laws of Motion. If he could measure the position and momentum of every particle in the universe and then apply his Laws of Motion to calculate how they interact, he could predict, in principle, the future of the universe in complete detail! A clockwork universe. What an elegant victory for science that would be! Truly a shame that it didn't work out that way.

Moses: What do you mean?

Socrates: As it turns out, his Laws of Motion worked brilliantly for calculating the exact orbit of two heavenly bodies circling each other, like the earth and the sun. But unfortunately, neither Sir Isaac nor any of his colleagues could find an exact solution for more than two bodies. Which is a pity, since last time I checked, our solar system has a few more than just two bodies.

Moses: So what happened?

Socrates: It became known as the Three Body Problem. Put a third heavenly body into the solar system, and not even the great Sir Isaac himself could find an exact solution to the equations describing their orbits. It caused quite a stir at the time.

Moses: Why?

Socrates: Because universities such as Cambridge were deeply religious institutions back then. In fact, to hold the Lucasian Professorship there, Sir Isaac had to be an ordained minister in the Church of England.

Moses: Even so, why did the Church care so much about this Three Body Problem?

[6] **Sir Isaac Newton** (1642 – 1727).

Socrates: At the time, the Church was still smarting over having to admit that the sun, not the earth, was at the center of the solar system. So when Sir Isaac discovered the Laws of Motion governing the solar system, it softened the blow a bit. That is, even though God hadn't placed his favorite species at the center of the solar system, at least he had created man enough in his own image to be able to comprehend the sublime elegance of how His creation worked. Not such a bad fallback position for the Church. But if the Three Body Problem had no exact solution, then it showed that man's understanding of the workings of the universe was incomplete at best, and dangerous at worse.

Moses: Why dangerous?

Socrates: If the orbits of more than two bodies cannot be predicted with mathematical certainty from Sir Isaac's Laws of Motion, then it's possible that heavenly bodies like the earth might someday leave their orbits and go flying off into space.

Moses: Seems like a pretty esoteric concern, given that the sun has been pretty consistent so far about rising and setting from the creation of the solar system!

Socrates: True, but people were considerable more superstitious in those days, especially about cosmic events. Comets and eclipses raised genuine concerns about the stability of the solar system and stoked a fear of earthly devastation. Take William [7], for example, who succeeded Sir Isaac as the Lucasian Professor at Cambridge. He first came to Sir Isaac's favorable attention because of his theory that comets colliding with the earth were responsible for the major events such as the biblical flood. But later, when he kept bringing up the Three Body Problem, Sir Isaac decided that he'd had enough. In fact, Sir Isaac treated him rather shabbily.

Moses: How so?

Socrates: First, he used his influence to have William stripped of the Lucasian Professorship, ostensibly for holding unorthodox religious views. And in 1720, when William was proposed for Fellowship in the Royal Society, Sir Isaac threatened to resign if he was elected. Needless to say, his application was dropped.

Moses: So what happened? How long did it take for someone to finally solve the Three Body Problem?

Socrates: A few centuries.

Moses: Centuries! Really?

Socrates: It had so frustrated the world's greatest mathematicians that in 1889, King Oscar II of Sweden, an amateur mathematician himself, offered a prize of 2,500 Swedish kronors to whoever could solve the Three Body Problem.

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[7] **William Whiston** (1667 –1752) was an English theologian, historian, and mathematician, a leading figure in the popularization of the ideas of Isaac Newton. He succeeded his mentor Newton as Lucasian Professor of Mathematics at the University of Cambridge, but in 1710 lost the professorship and was expelled from the university as a result of his unorthodox religious views.

Moses: And did someone finally solve it and win the prize?

Socrates: Henri[8] won the prize, but hardly in the way that Sir Isaac had hoped.

Moses: How so?

Socrates: Rather than finding the solution to the Three Body Problem, Henri proved instead that no exact solution existed. That is, he proved that the orbits of the planets are not completely predictable, the solar system cannot be unequivocally be counted on to be stable, and heavenly bodies could suddenly fly off course!

Moses: Sounds like the mathematical proof of Armageddon.

Socrates: It certainly distressed a great many people. But Henri was right. In fact, it happens with asteroids all the time.

Moses: You're kidding.

Socrates: Nope. Ever heard of Kirkwood gaps?

Moses: What are they?

Socrates: Forbidden zones for asteroids in the solar system. Daniel [9] discovered them in 1857. An interesting chap, Daniel. He started out as a high school teacher who had taught himself algebra in order to be able to teach his students. In the process, he discovered that he had a real knack for mathematics, so much so that he eventually become a professor at Indiana University. He was likewise fascinated by astronomy, and noticed that the asteroid belt in the solar system had gaps at regular intervals between the orbits of Mars and Jupiter. Even more curious, the spacing of the gaps corresponded to small whole number ratios of the orbital period of Jupiter, which is 11.86 Earth years.

Moses: What's the explanation?

Socrates: It has to do with Keppler's third law, which states that the orbital period of a planet or asteroid is proportional to its distance from the sun. One of the Kirkwood gaps, for example, was at distance from the sun corresponding to an orbital period with a 3:1 ratio to Jupiter's orbital period – that is, a bit under four years.

Moses: How does that explain the gap?

Socrates: Because an asteroid in that gap would pass by Jupiter at exactly the same three positions in space on its successive orbits of the sun. Because Jupiter is very large, the asteroid's orbit is disturbed by Jupiter's gravitational pull each time it passes one of these three points. The cumulative sling shot effect of this resonance eventually

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[8] **Henri Poincaré** (1854 –1912) was a French mathematician, theoretical physicist, engineer, and philosopher of science, often described as a polymath who made many original fundamental contributions to pure and applied mathematics, mathematical physics, and celestial mechanics. In his research on the three-body problem, Poincaré became the first person to discover a chaotic deterministic system which laid the foundations of modern chaos theory. He is also considered to be one of the founders of the field of topology.

[9] **Daniel Kirkwood** (1814 –1895)

accelerates the asteroid enough to eject it from its orbit, causing it to either fly in towards the sun or out of the solar system, occasionally colliding with a planet in the process.

Moses: Fascinating. Could it happen to the earth too?

Socrates: The good news is that the Earth's ratio isn't exactly twelve to one – as we said, it's 11.86 Earth years to one Jupiter year. Also, Earth is also much closer to the sun, so that Jupiter's gravity has a weaker effect. So if it hasn't happened yet after billions of years since the solar system first formed, we are probably safe, at least in our own lifetimes.

Moses: That's encouraging. What exactly did Henri do to prove that the Three Body Problem had no solution?

Socrates: He discovered chaos.

CHAPTER 3: A Universe of Chaos

Moses: What do you mean, he discovered chaos?

Socrates: Not the kind of chaos that's afflicting your personal life right now.

Moses: Very funny.

Socrates: I'm talking about chaos in the mathematical sense.

Moses: So I gathered. Tell me about it.

Socrates: Mathematical chaos refers to random-appearing behavior that, despite its irregularity, is not random. Instead, it's governed by exact, deterministic rules. It really wasn't until modern computers came along that Henri's discoveries about mathematical chaos could be fully explored and appreciated. But the Three Body Problem is one example that Henri was able to tackle before computers were available.

Moses: How does mathematical chaos work?

Socrates: I'll give you a simple example. Do you know the equation for a parabola?

Moses: Not offhand.

Socrates: It's pretty simple: $y = a \cdot x \cdot (1-x)$. Close your eyes for a second.

Moses: Why?

Socrates: So I can show it you. I'll project it into your mind.

Moses: You can do that?

Socrates: Of course. Are you really surprised? After all, you've been discussing philosophy with a sea lion. If you've made that leap of faith, this should be a piece of cake! Now go ahead - close your eyes so that you can see the graph.

Moses: OK, my eyes are closed.

Socrates: What do you see?

Moses: It's a smooth curve that starts at zero for *x*=0, rises to a peak and then falls back to zero at *x*=1 (Figure 3-1).

Socrates: Very good. Now for the interesting part. It turns out that the parabola is the solution another useful

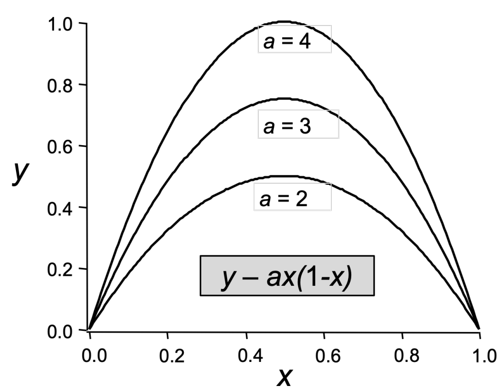

Figure 3-1. Graph of the equation for a parabola: $y = a \cdot x \cdot (1-x)$ for $x=0$ *to 1*
The parameter *a* controls the amplitude of the parabola.

equation called the logistic equation.

Moses: What's the logistic equation?

Socrates: It's a nonlinear mathematical equation that was developed by scientists to study how populations evolve from generation to generation, among other things. Mathematically, it can be written as [10]:

$$x_n = a \cdot x_{n-1} \cdot (1 - x_{n-1})$$

where x_n is the new value of x computed from its previous value x_{n-1}. n is the number of times you've iterated the equation, for as long as you have the patience to continue. You start by choosing an initial input value x_0 between zero and one, and plug it into the equation to calculate the output value x_1. Then you input x_1 back into the equation to get the next output value x_2, and so forth.

Moses: Okay, but I haven't seen anything chaotic so far.

Socrates: Close your eyes again. How about this (Figure 3-2A)? I set the value of *a* to four in the equation. Then I chose the initial value of *x* to be 0.6, and plotted x_n versus *n* for sixty iterations.

Moses: Now that looks random, for sure.

Socrates: But it's not. Like I said, I calculated it directly from the logistic equation, which has nothing random about it. It's completely deterministic.

Moses: Not to impugn your character, but sea lions are not exactly known for their mathematical prowess. How do I know that you didn't just make up the data in the graph?

Socrates: Because I can prove it to you. Let's plot the data in a different way, called a Poincaré plot, in honor of Henri. The idea is to plot the current value of *x* against its previous value – that is, the second value against the first, the third

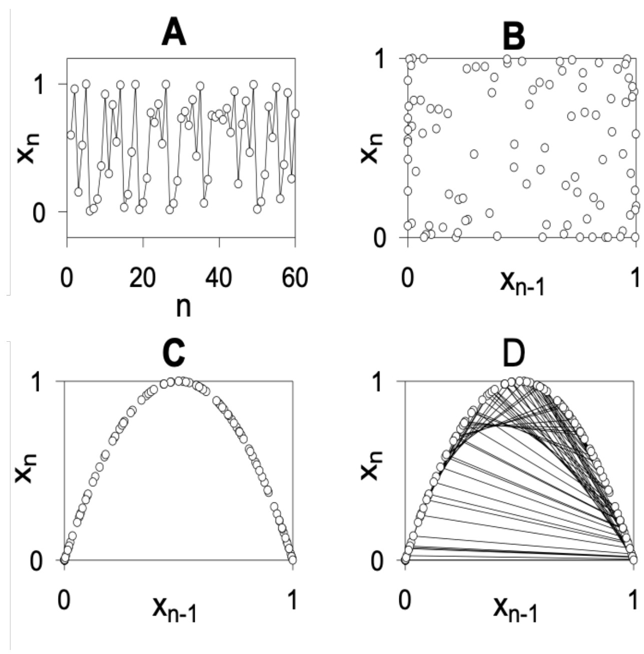

Figure 3-2. Mathematical chaos generated by the logistic equation. A. A graph showing how the value of *x* changes chaotically with each iteration *n* of the logistic equation, for *a*=4.0 and a starting *x* value of 0.6. **B.** Poincaré plot of the current value of *x* (x_n) versus its previous value (x_{n-1}) for a random process. **C.** Poincaré plot of the current value of *x* (x_n) versus its previous value (x_{n-1}) for the data generated by the logistic equation in A. **D.** Same as C, but with the successive data pairs connected by lines.

[10] This is the discrete form of the logistic equation, rather than the continuous differential equation form whose solution is a sigmoid function rather than a parabola.

against the second, the fourth against the third, as so forth. It's a way of asking a simple question: is the value of x_n related to its previous value x_{n-1}? If there is no relationship, then the graph will show a diffuse cloud of points, with no distinct pattern visible (Figure 3-2B). In that case, you might as well attribute the behavior to random factors. But if the points on the graph fall into a highly structured pattern, it means the current value is x_n has been *determined* in some way by its previous value x_{n-1}. In other words, the relationship can't be random and must be deterministic chaos instead.

Moses: What does the Poincaré plot show for the actual data from the logistic equation?

Socrates: Close your eyes again.

Moses: Ah, yes, there is a relationship (Figure 3-2C) - all of the points fall on a parabola!

Socrates: Exactly. Despite the completely irregular, random-appearing pattern, all of the actual data points fall on a parabola. What creates the irregular sequence in the graph of x_n versus n (Figure 3-2A) is that the points constantly jump around the parabola, sometimes staying on the upward sloping portion several times in a row, and then suddenly jumping to the down-sloping portion, and vice versa. You can see it when connect the successive points on the Poincaré plot with lines (Figure 3-2D). Sometimes the lines cross back and forth across the parabola and other times they stay on the same side.

Moses: That's fascinating - such a simple mathematical equation producing such complex behavior! Is it just a mathematical curiosity, or does it have any real world significance?

Socrates: What do you think?

Moses: I suppose that if you had real world experimental data points showing an irregular pattern, and found that all of the points fell on a parabola when you plotted them on a Poincaré plot, it would tell you that irregular behavior can't be random.

Socrates: Exactly!

Moses: But so what? How does knowing whether the data points fall on the curve of a parabola tell me anything useful about what's going on.

Socrates: What if you wanted to change the behavior – to make it regular instead of irregular?

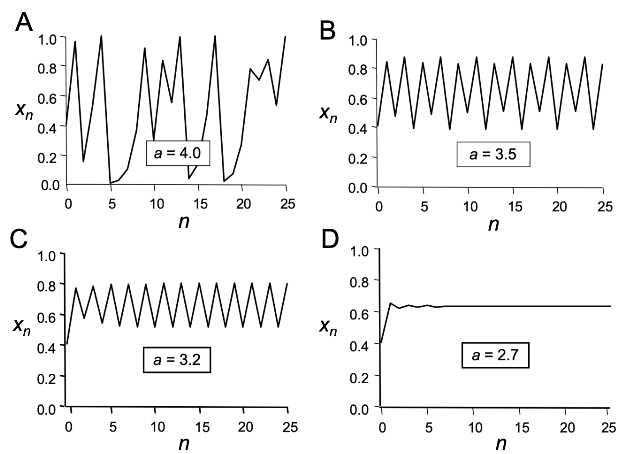

Figure 3-3. The behavior of the logistic equation for different values of *a*. A. Chaotic (aperiodic) behavior for *a*=4.0. B. Repeating every 4th value (period-4) behavior for *a*=3.5. C. Alternating (period-2) behavior for *a*=3.2. D. Stable (period-1) behavior for *a*=2.7.

Moses: How?

Socrates: It turns out that the value of *a* in the logistic equation directly determines whether the behavior is irregular or not (Figure 3-3). For example, if you reduce the value of *a* from 4.0 to 3.5, the irregular chaotic behavior disappears and settles into a regular pattern of four repeating values, ABCDABCDABCD…. (Figure 3-3B). If you lower *a* further to 3.2, x_n alternates between a large value and a small value on subsequent iterations, ABABABAB….(Figure 3-3C). And if you lower *a* to 2.7, the behavior becomes completely stable, AAAAA….. (Figure 3-3D). It's known as a period-doubling route to chaos.

Moses: But why is the value of *a* so important?

Socrates: Because *a* is like a gain factor that acts on the other two terms in the logistic equation, which are positive and negative feedback terms, respectively. The value of *a* controls the level of feedback.

Moses: What's that supposed to mean?

Socrates: Tell you what – how about I illustrate it with an example? What's your favorite food?

Moses: If I had to choose one, I'd say fish.

Socrates: What a coincidence, mine too! Herring, especially. Let's talk herring then. My sea lion buddies always complain to me about how unpredictable the herring population is from year to year. Sometimes the herring are plentiful and other times they're scarce, so they never know whether they'll be feasting or fasting. Of course, being sea lions, they just have to put up with it. But what if you humans, clever creatures that you are, measured the herring population each year and made a Poincaré plot. And what if the Poincaré plot demonstrated that the herring population from one year to the next year fell on a parabola?

Moses: You mean a steep parabola in which the gain factor *a* was more than 3.87?

Socrates: Exactly, since that's the threshold for chaos to explain the completely irregular behavior. Now suppose that you humans wanted to do the sea lions a favor and stabilize the herring population so their food supply was more consistent from year to year. How might you go about it?

Moses: Theoretically, if the gain factor *a* could be lowered to a value below 2.7, that would do it. According to your graph (Figure 3-3D), a value of 2.7 would convert the chaotic behavior to a stable herring population from year to year.

Socrates: Very good, Moses, that's right!

Moses: Except that I have no idea how to go about lowering the value of *a.* It's just a letter of the alphabet, and last time I checked, herring can't read.

Socrates: Then let's try to figure it out. Take the first part of the logistic equation, $a \cdot x_{n-1}$. What influence does the value of *a* have on the next year's herring population of x_n?

Moses: A higher value of *a* will cause the next year's herring population to be greater than this year's.

Socrates: Exactly – the larger the herring population this year, the more baby herring will be born to increase the herring population next year. That's the positive feedback factor, whose gain is *a*. In this case, we can infer that *a* is strongly influenced by the fertility rate of the herring.

Moses: What about the next part of the logistic equation, (1- x_{n-1})?

Socrates: That's the negative feedback factor. For example, if there was a large herring population last year, there was plenty of food for sea lions. That means more sea lions will have survived into the current year. With more sea lions around, however, more herring will be eaten, decreasing the number of herrings surviving to the next year. Can you guess what happens after that?

Moses: I suppose that with fewer herring next year, fewer sea lions will survive into the year after that, allowing the herring population to rebound.

Socrates: Exactly, and so the cycle it continues. The gain factor *a* determines how sensitive the herring population is to the positive and negative feedback factors like fertility rates and number of sea lion predators eating the herring.

Moses: Then if the herring fertility rate decreased, so that the herring population couldn't respond as quickly to changes in the numbers of predators, that would decrease *a* and stabilize both populations. Or if sea lion fertility decreased, so that the predator population didn't expand as quickly when herring population increased, it would also decrease *a* and have a stabilizing effect.

Socrates: Exactly, you've got it! The positive and negative feedback factors have to be in a natural balance for the herring and sea lion populations to remain stable. That's why diagnosing chaos is important – unlike purely random processes in nature, chaos follows rules that can give you insights into how to change the behavior. The sea lion-herring example is a classic predator-prey situation. Admittedly, the logistics equation is a bit oversimplified for representing it mathematically. But mathematicians can write more specific equations that directly incorporate herring and sea lion fertility rates and other relevant factors into the predator-prey dynamics. In fact, there are many real world situations in which your human colleagues have used mathematical equations similar to the logistic equation to account for predator-prey relationships [11], chaotic population variations, how epidemics spread and numerous other examples.

Moses: So once I have made enough measurements to come up with the correct value for *a* in the logistic equation, or the equivalent parameters in more detailed equations, I can then predict how the herring population will change each month from then on,

[11] The lynx and snowshare hare populations in North America have a predator-prey relationship. Disease, food supply and other predators are variables in this complex relationship that results in an 8-11 year cyclical flux in the both populations.

right? I can plug the right equations into the computer, and predict the herring population reliably from then on!

Socrates: You might think so, but it's not that straightforward when the population is varying chaotically. Even if you have the correct parameter values for your equations, your computer can only perform calculations to finite number of decimal places. Eventually, the computer has to round off the numbers, before it can plug them back into the equation to compute the next value.

Moses: Why does that matter? Scientists are always rounding off numbers when they use mathematics to solve problems.

Socrates: It depends on the real world problem that you're trying to solve. When chaos is involved, it's a different ball game.

Moses: What do you mean?

Socrates: Let's go back to logistic equation again. Suppose that we had measured the herring population for many years and knew the exact value of *a* in the logistic equation to predict this year's population from last year's population. Suppose also that the maximum herring population in our region of the ocean were ten million, and that we measured last year's population at exactly six million. You might think that we could then predict exactly how the herring population would change from that year on, using the logistic equation, and wouldn't need to actually measure the population any longer. But suppose that we had made a very small mistake, and there was one herring hiding under a rock that we missed. If you plug 0.6000001, instead of 0.6000000, as the starting value of *x* into the logistic equation, a difference of one herring in six million, and then make the same plot, the results are similar for the first thirty years or so, but after that, they diverge, producing a completely different pattern (Figure 3-4A). But if you make the Poincaré plot (Figure 3-4B), all the points still fall on the same parabola.

Moses: So I'd still have to count the number of herring every now and then to keep my predictions accurate. That is, I could only accurately predict the population for a limited period of time.

Socrates: I'm afraid so. It's a defining feature of chaos, called "sensitive dependence on initial conditions," also known as "the butterfly effect."

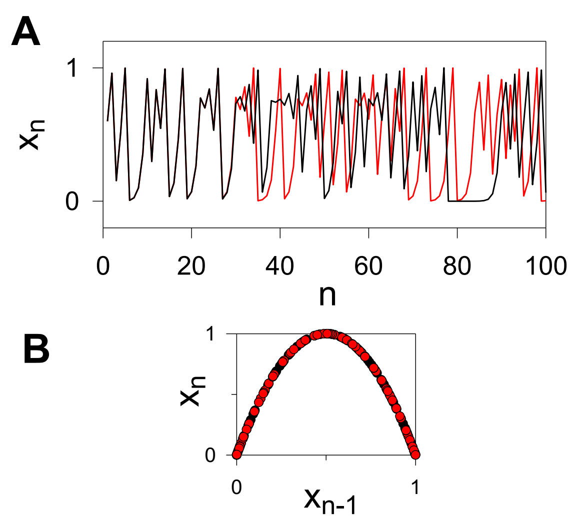

Figure 3-4. Sensitivity to initial conditions. A. Same herring population as in Figure 3-2, starting with either 6,000,000 herrings (black lines) or 6,000,001 herrings (red lines) in the first year. The black and red curves diverge completely after 30 years, even though all of the black and red data points fall on the same curve in the Poincaré plot shown below in **B**.

Edward[12] discovered it in the 1960s. He was a meteorologist working on mathematical models of the atmosphere to try to predict the weather. Linear models were not working well, so I nudged him to give nonlinear models a try. After running one simulation on his computer, he wanted to confirm the results. To save time, I convinced him to reenter the data from a printout of the results from midway through the first computer run, rather than restart the program from the beginning. When the final results came out, however, he was surprised that they were completely different. It was quite puzzling, since the equations in the model were exact, with no randomness, just like the logistic equation.

Moses: How did that happen?

Socrates: It was the chaotic output of his weather equations exhibiting "sensitive dependence on initial conditions." As he eventually discovered, his computer had performed the calculations to six digits precision, but in the printout, they were rounded off to three digits, for example from 0.506 instead of to 0.506127. Over time, this small difference made a big difference to the calculations. He called it the "butterfly effect," after the idea that if a butterfly flapped its wings, the small air currents could change initial conditions enough to produce a completely different weather pattern – for example, causing a hurricane that otherwise would not have occurred.

His discovery proved that because of chaos, it will never be possible to predict the weather accurately for more than a week or so. A long way from the clockwork universe whose weather Sir Isaac had hoped could be predicted forever.

Moses: What you're really saying is that unless you have a computer that can do calculations to infinite precision and never round off the number of decimal places, you can never really know the true behavior of even a simple equation like the logistic equation when it's producing chaos.

Socrates: Exactly, you can only approximate the behavior for a limited period of time – after that, it diverges into the unknown.

Moses: What causes this "sensitive dependence on initial conditions?"

Socrates: It's because during chaos, small differences get magnified exponentially. Most people don't appreciate how quickly exponential differences grow. A great example is the parable about the Chinese peasant who saved the Emperor's life. Do you know it?

Moses: Sounds vaguely familiar.

Socrates: It goes like this. The Emperor wanted to reward the peasant for saving his life. After thinking about it, the peasant made a seemingly modest request. To provide

[12] **Edward Norton Lorenz** (1917–2008) was an American mathematician and meteorologist who established the theoretical basis of weather and climate predictability, as well as the basis for computer-aided atmospheric physics and meteorology. He is best known for his seminal contributions to modern chaos theory.

rice to feed his family, he humbly asked the Emperor to place one grain of rice on the corner square of a chess board, two grains on the adjoining square, four grains on the next square and so forth, doubling the number of grains of rice on each new square, until all sixty-four squares of the chess board had been filled. The Emperor, thinking the peasant a fool for asking for such a modest reward, readily granted his wish, and had his servants begin the process. As his servants carted more and more bags of rice into the palace, it soon became apparent that with sixty-four squares on the chess board, the number of grains of rice on the last square (2^{64}= a hundred billion billion) came to more rice than existed in the whole empire. The clever peasant had outsmarted the Emperor.

Moses: What did the Emperor do?

Socrates: Legend has that he beheaded the peasant for his impertinence.

Moses: Ouch! Too smart for his own good, I guess.

Socrates: Here's another example you'll like. Suppose I were to take a sheet of typing paper and fold it in half, and then in half again, and so forth, until I had folded it fifty times. If I could do this, how thick would the sheet of paper now be?

Moses: I don't know, maybe it would reach the ceiling.

Socrates: Keep going.

Moses: Really? How about the height of a building?

Socrates: Keep going.

Moses: Okay, how about Mt. Everest?

Socrates: Would you believe past the moon?

Moses: Not possible. That's ridiculous.

Socrates: Well, it's easy to calculate. If the paper is 0.1 mm thick, and it doubles each time you fold it in half, that comes to 0.1 mm times 2^{50}, which is around 110 million kilometers, or three quarters of the way to the sun. One more fold and you'd be past the sun! Actually, to reach the moon, you would only need to fold the sheet of paper in half twenty-seven times. Much simpler than building a space ship!

Moses: That's pretty amazing!

Socrates: I know. That's the power of exponential growth. The same thing happens in chaotic systems - small differences get magnified exponentially, so the differences become very large very quickly. That's explains why the tiny air currents from a butterfly flapping its wings could change the weather across the globe ….and why longterm weather forecasting will always be unreliable.

Moses: So we'll never be able to predict the weather accurately for more than a week or so, and our solar system may suddenly fly apart someday because the Three (or more) Body Problem has no exact solution.

Socrates: That, my friend, is why the discovery of chaos was the first nail in the coffin of

Sir Isaac's dream of a clockwork universe.

Moses: Are you implying that there's a second nail as well?

Socrates: Indeed. As it turns out, even if we could calculate everything to absolute precision, which we can't, we still wouldn't be able to experimentally measure anything with perfect precision. That's the second nail.

CHAPTER 4: Quantum Weirdness

Moses: Why can't we experimentally measure anything with perfect precision?

Socrates: It's Protagoras's "Man is the measure of all things" coming back to haunt us. Everything in this world is interconnected to everything else. As part of the real world, humans can only make measurements with real measuring devices. But every time you make a measurement, your measuring device perturbs what you are measuring, and changes the future in some unpredictable way.

Moses: You are referring to quantum physics, I take it.

Socrates: The very same. That's the second nail in the coffin for Sir Isaac's clockwork universe, at least as far as humans are capable of comprehending it. Fortunately, quantum effects don't really matter much for large objects, such as planets, or even small objects like grains of sand. But for very, very small objects like atoms and subatomic particles, they play a big role in creating uncertainty. And ultimately, since large objects are composed of subatomic particles, they also contain the same uncertainties. Not normally enough to cause any major errors at the scale of our everyday world, but enough to make perfect accuracy impossible to achieve.

Moses: How?

Socrates: Take electrons, for example. You probably think of them as little negatively-charged particles, like billiard balls, flying around in space. But that's not correct according to quantum physics - they also have wave-like properties.

Moses: Why does that matter?

Socrates: Think of a wave in the ocean. Is it located in just one place?

Moses: No, it's spread out over a wide area.

Socrates: Correct, so just like you can't really define an ocean wave as existing at one point in space, the part of the electron that's wave-like is distributed over space – wave-particle duality, in the parlance of quantum theory.

Moses: So does that mean that you can never say exactly where an electron is located?

Socrates: That is the crux of the problem….. and not just for electrons, but for all subatomic particles. Even though physicists call them particles for convenience, they really should be thought of as particle-waves. The issue is called the Heisenberg Uncertainly Principle – the simultaneous position and momentum of a subatomic particle at a given point in time can never be precisely determined. The more precisely you determine the particle's position, the less you know about its momentum and vice versa. Technically speaking, the product of the uncertainty in the particle's position and momentum always exceeds Planck's constant divided by two. It's true that Planck's constant is very small (6.6×10^{-34} J-s), so that the effect is trivial for large objects. But it becomes very prominent at the atomic and subatomic scales. And if you have chaos and sensitivity to initial conditions, like in the Three Body Problem, any uncertainty gets magnified exponentially.

Moses: Which means that no matter how small the error, if it grows exponentially, it won't take long to become significant - like folding that sheet of typing paper in half 27 times to reach the moon.

Socrates: Exactly. Even if you had a computer that could do calculations to infinite precision, which we already said is impossible, you still couldn't calculate the future of a solar system when the Uncertainty Principle meets mathematical chaos, like in the Three Body Problem. And that's not the only issue with quantum physics.

Moses: What else?

Socrates: There's also the *"God doesn't play dice with the universe"* problem that frustrated Albert [13] so much.

Moses: Why?

Socrates: Because in quantum physics, the equation that governs the behavior of a subatomic particle, called the Schrödinger equation after Erwin [14], contains a wave function Ψ that describes the probability over time that a subatomic particle will be in one quantum state or another should you try to measure it. In other words, you cannot predict with certainty which state it will be in – the best you can do is calculate the probability that it will be in any given state. It's like the particle exists in all possible quantum states simultaneously, and only when someone tries to measure it does the particle assume a single well-defined quantum state. Quantum physicists call it "the measurement problem" – that somehow the act of measurement causes the wave function in the Schrödinger equation to "collapse" from a probability distribution into a definite quantum state. What it all means physically is still mysterious to this day [15]. As

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[13] **Albert Einstein** (1879 –1955). His famous quote expresses his displeasure with quantum theory replacing certainties with probabilities.

[14] **Erwin Schrödinger** (1887–1961) was a Nobel Prize-winning Austrian-Irish physicist who developed a number of fundamental results in quantum theory, including the **Schrödinger wave equation** describing a subatomic particle's time evolution. Ψ is the probability amplitude, with real and imaginary components corresponding to the wave's amplitude and frequency. The actual probability of the quantum particle being in one quantum state or another at a given point in time is given by the multiplying Ψ by its complex conjugate Ψ^*. To observe which quantum state the particle is in, however, requires a measurement which collapses the Ψ function to either one quantum state or another. That is, until the measurement is made, you don't know which quantum state the particle will choose.

[15] The controversy over how to interpret wave function collapse in the **Schröinger wave equation** is known as **the measurement problem**. Its implications are broad, including the very nature of time itself. The Nobel laureate **Ilya Prigogine** has argued that this is the key to resolving quantum mechanics with the Second Law of Thermodynamics, which states that the entropy (level of disorganization) of the universe increases irreversibly. That is, if all quantum events are driven by random probability of particles choosing one state or another as time moves forward, then reversing time would lead to a different set of random choices, and hence would not recreate the past. This destroys the symmetry of time – that, time running backwards would not be able to recreate the lower entropy state of the past.

Niels [16] put it, *"Whoever is not shocked by quantum theory has not understood it."*

Moses: Where do things stand now?

Socrates: Most physicists have thrown up their hands and subscribe to what's known as the Copenhagen interpretation.

Moses: What's that?

Socrates: It's the interpretation championed by Niels and his colleagues, who concluded that the collapse of the wave function in the Schrödinger equation is a mathematical description that has no direct physical interpretation in our everyday world [17]. Not surprisingly, other physicists, including Albert, found that explanation, or lack of explanation, deeply troubling. That's what prompted Albert's famous *"God doesn't play dice with the universe"* quote. Of course, if God is responsible, then He can play by whatever rules He wants to, so Albert had no real basis to complain. That's basically what Niels meant when he responded to Albert with *"Stop telling God what to do*."

Moses: I thought that we agreed to keep God out of this.

Socrates: My apologies. Just saying.

Moses: Is quantum theory really supported by solid experimental evidence?

Socrates: By more than a few Nobel prize-winning experiments.

Moses: Like what?

Socrates: My personal favorite is the double slit experiment, where subatomic particles like electrons are fired, one at a time, towards two slits in a metal plate (Figure 4-1). When you tape over one of the slits and then fire an electron at the plate, then assuming the electron makes it through, it appears on the other side opposite the open

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[16] **Niels Bohr** (1885–1962), Danish physicist and philosopher who made foundational contributions to understanding atomic structure and quantum theory, for which he received the Nobel Prize in Physics in 1922.

[17] For thorough discussion, see **Adam Becker's** *What is Real? The Unfinished Quest for the Meaning of Quantum Physics.* Basic Books, 2018. In more recent work (see https://en.wikipedia.org/wiki/Quantum_decoherence) "The lack of observability of probabilistic quantum events at supra-atomic scales has been attributed to quantum decoherence, in which the coherence of the wave function degrades over time as the subatomic particle interacts with its environment, for example during measurements. If a quantum system were perfectly isolated, it would maintain coherence indefinitely, but it would be impossible to manipulate or investigate it. If it is not perfectly isolated, for example during a measurement, coherence is shared with the environment and appears to be lost with time. As a result of this process, quantum behavior is apparently lost, just as energy appears to be lost by friction in classical mechanics. Decoherence has been used to understand the collapse of the wave function. Decoherence does not generate actual wave-function collapse. It only provides an explanation for apparent wave-function collapse, as the quantum nature of the system "leaks" into the environment. That is, components of the wave function are decoupled from a coherent system and acquire phases from their immediate surroundings. A total superposition of the global or universal wavefunction still exists (and remains coherent at the global level), but its ultimate fate remains an interpretational issue. Specifically, decoherence does not attempt to explain the measurement problem. Rather, decoherence provides an explanation for the transition of the system to a mixture of states that seem to correspond to those states observers perceive."

slit, as you would expect. But here's the puzzling part. When you remove the tape from the second slit and then fire the electrons one at a time, where do you think they appear?

Moses: You'd think that they'd appear opposite both slits (Figure 4-1A).

Socrates: That's what you'd expect if the electrons acted purely as particles, like in classical physics. But in quantum physics, wave-particle duality kicks in and that's not what happens.

Moses: Because of their wave-like component?

Socrates: Exactly. Think of light waves. What would happen if you shined a light at the two slits?

Moses: I suppose that a light beam would produce an interference pattern on the opposite side, with a series of illuminated lines separated by dark regions (Figure 4-1B).

Socrates: Correct. That's because as light waves go through the two slits, the peaks and troughs of the waves interfere and cancel each other at regularly spaced intervals, which generates the interference pattern. Even when you fire single photons one at a time, they will still create the same interference pattern over time, with each photon that gets through the slits landing unpredictably on one of the many lines on the opposite side.

Moses: So you're saying that because of its wave-like properties, an electron behaves the same way as a photon?

Socrates: Exactly. When the second slit is open, the electrons don't appear exclusively

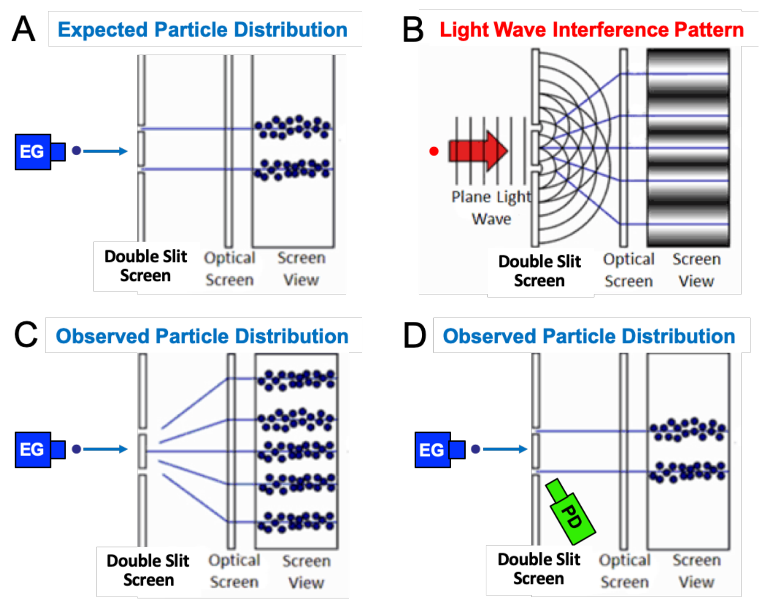

Figure 4-1. The double slit experiment in quantum physics. A. In classical physics, electrons fired from an electron gun (EG) towards two slits would be expected to go through one slit or the other, as predicted for pure particles. **B.** In contrast, when light is shined through two slits, an interference pattern results, as predicted for pure waves. **C.** In real experiments, however, electrons fired towards two slits create an interference pattern, even if the electrons are fired one electron at a time. **D.** If a particle detector (PD) measures which slit the electron goes through, the interference pattern disappears. Quantum theory is required to explain these findings as a manifestation of wave-particle duality.

opposite the two slits. They start to appear at many other locations as well, because the wave portion of the electron creates an interference pattern (Figure 4-1C). In other words, you can't predict where any individual electron will appear. All that you can say is after firing hundreds of electrons, you will begin to see an interference pattern, as predicted statistically by quantum theory.

Moses: Bizarre. Each electron somehow chooses, but we can't know what choice it will make?

Socrates: Actually, it's even more bizarre than that.

Moses: How so?

Socrates: If you place a photodetector (PD) to detect which slot the electron passes through as it whizzes by, then the interference pattern disappears (Figure 4-1D)!

Moses: How does that make any sense? How can the wave-like behavior evaporate just because you measure which slit the electron has passed through?

Socrates: Because by detecting the electron as it passes through the slit, you've caused its wave function to collapse, and now the electron behaves like a particle. It's very bizarre.

Moses: And this same phenomenon happens with all subatomic particles?

Socrates: Even light, which has no mass. Light also behaves like a particle and a wave at the same time. That's what won Albert his 1921 Nobel Prize, for showing that light had to be a collection of discrete wave packets (photons), rather than a pure wave, in order to explain the photoelectric effect [18]. It was a key point that contributed to the foundation of quantum physics.

Moses: It's still hard for me to understand how something like an electron or a photon can be both a particle and a wave at the same time. And it totally boggles the mind to think that a subatomic particle exists as a mixture of quantum states until an observer makes a measurement forcing it to choose one state over another. It's like the observer is unwittingly changing the course of the universe every time he or she makes a measurement. Are you sure that there's no way around the random uncertainty aspect?

Socrates: That's what Albert was searching for – hidden variables to explain the uncertainty. That is, the behavior appears random to us because key hidden variables, which are invisible to us, are operating behind the scenes. But that possibility was also

[18] The **photoelectric effect** refers to the emission of electrons when light hits the surface of a material. According to classical physics, the photoelectric effect can be attributed to the transfer of energy from the light to an electron. However, the experimental results do not correlate with predictions made by classical theory assuming the light is entirely wave-like. Based on the finding that a low-frequency beam at a high intensity cannot build up the energy required to eject electrons like it would if the light's energy were continuous like a wave, Einstein proposed that a beam of light is not a wave propagating through space, but rather a collection of discrete wave packets (photons).

later excluded by some very clever experiments involving quantum entanglement [19]. Most physicists nowadays think that the uncertainty is a fundamentally irreducible feature of reality.

Moses: There's no way around it?

Socrates: Some pretty creative theories have been proposed.

Moses: Like what?

Socrates: Superstring theories, for example. Especially in its latest version, called M theory [20].

Moses: How do they explain it?

Socrates: By envisioning subatomic particles as vibrating strings of energy.

Moses: I guess that accounts for the name. How does that help?

Socrates: Instead of imagining a subatomic particle existing at a point in space, the superstring theorists imagine it as a vibrating string of energy – with the vibrations of the string generating the wave-like properties. The strings can be open or closed (Figure 4-2) depending on which subatomic particles they represent. Think of the analogy to a guitar string - if you were to stretch a guitar string between two fixed points, the length and tension of the string would determine the fundamental frequency at which it vibrates. Shorter strings with higher tension vibrate at higher frequencies, and vice versa. Not only that, but when a string vibrates, it doesn't just vibrate at its fundamental frequency, but also at a whole series of higher frequencies called harmonics that correspond to the wavelengths that can fit between two ends of the string (Figure 4-2A). It's the same idea for a vibrating string of energy - if you imagine that each harmonic corresponds to a different "quantum state," a subatomic particle plays its fundamental tone and harmonic overtones simultaneously just like a plucked guitar string. In other words, the subatomic particle's vibrating string of energy exists as a simultaneous superposition of many quantum states, just like the

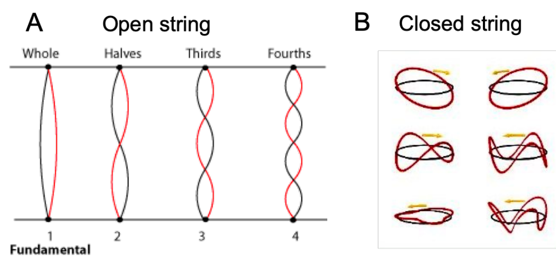

Figure 4-2. Vibrating string harmonics for open (A) and closed (B) strings. If the distance between the ends of the string is *d,* then the string can vibrate at wavelengths corresponding to *d* (fundamental)*, d*/2 (halves)*, d*/3 (thirds), *d*/4 (fourths), and so forth, called harmonic overtones.

[19] **Quantum entanglement** experiments testing Bell's Inequality ruled out the hidden variables explanation. For the interested reader, see **Adam Becker,** *What is Real? The Unfinished Quest for the Meaning of Quantum Physics* by (Basic Books, 2018).
[20] See **Brian Greene,** *The Elegant Universe* (Norton, 1999) and Wikipedia http://universe-review.ca/R15-18-string05.htm.
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the wave function in Schrödinger equation predicts!

Moses: Very clever analogy. What about the collapse of the wave function? How does that fit in with a vibrating guitar string?

Socrates: I think of it this way. Imagine you took a snapshot of a vibrating guitar string with a highspeed camera. What would you see in the photograph?

Moses: It would depend on the exact timing of snapshot, I suppose. When the amplitude of the fundamental frequency happens to be large, the vibration pattern in the snapshot will be dominated by the fundamental frequency. When the amplitude of the fundamental frequency is low, however, the pattern looks more like one of harmonic overtones.

Socrates: Exactly. Now imagine the same thing for the vibrating string of energy. Depending on when you measure it, sometimes its amplitude will be dominated by one harmonic (representing a particular quantum state) and sometimes by another (representing a different quantum state). Until the measurement is made, you don't know which quantum state will happen to be predominating at that moment. That's one intuitive way of imagining what happens when the wave function collapses.

Moses: But what's holding these subatomic vibrating strings in place, so that they have enough tension to vibrate?

Socrates: That's the most intriguing aspect of all. According to the theory, they're not actually tethered to the three dimensions of space that we're familiar with, namely right-left, up-down and in-out. Instead, the theory posits that the strings are tethered to hidden dimensions.

Moses: Hidden dimensions? Hiding where?

Socrates: Inside the fabric of space.

Moses: You're kidding me, aren't you?

Socrates: Nope, I'm serious.

Moses: Is that why it's called superstring theory, instead of just string theory, because of these other dimensions?

Socrates: Not exactly. String theory was originally developed to describe the particle-wave duality of subatomic particles, but an unexpected prediction that fell out of the theory was a subatomic particle in the form of a closed vibrating string of energy that was a natural candidate to transmit the force of gravity – the so-called graviton. Even though it was completely unanticipated, that finding set the stage for string theory to be combined with two other theories, supersymmetry and supergravity. That's where the super in superstring theory comes from. And from there, superstring theory led to M theory – a potential Theory of Everything that accounts for all of the known subatomic particles and unifies the electroweak and strong nuclear forces with quantum gravity.

Moses: Why did they need unifying?

Socrates: Because you have two of the most successful theories in the history of physics – General Relativity explaining gravity, and Quantum Mechanics explaining the other two fundamental forces of nature. But they conflict with each other.

Moses: How?

Socrates: General relatively assumes spacetime and the force of gravity are continuous – that is, they are both infinitely divisible, with no minimum size beyond which they cannot be further divided. Quantum mechanics, on the other hand, assumes that everything else in nature is quantized into small indivisible packets. Unless both theories are continuous or both are quantized, they can't be unified into a single Theory of Everything. So far, no one's been able to make both theories continuous. Indeed, that's why quantum physics arose in the first place, because classical Newtonian physics, which is continuous, couldn't explain the behavior of atoms and subatomic particles. Not even Albert could get around that, as hard as he tried! So the only alternative is to come up with a quantum theory of gravity to match the quantum nature of the other two fundamental forces of nature.

Moses: How?

Socrates: By quantizing space and gravity. In other words, if you need a quantized packet of energy like a photon to transmit electromagnetic force, then for a unified Theory of Everything, you also need a quantized packet of energy to transmit gravitational force. That's where gravitons, the subatomic particles mediating the force of gravity, come into the picture.

Moses: So how do these superstring and M theories do that?

Socrates: They start by postulating that if we could magnify the three space dimensions that we're familiar with to an extreme degree, we would find that space eventually appears granular instead of continuous, like a grid of very small packets of space on the order of Planck's length.

Moses: How long is that?

Socrates: Around 1.6 x 10^{-35} m. A billionth of a billionth of a billionth of a billionth of an inch. Or, if you prefer, a hundred billion billion times smaller than a single proton. Too small for anyone to visualize experimentally, obviously.

Moses: And that's where these hidden dimensions are lurking?

Socrates: That's the theory. The hidden dimensions are compactified and curled up inside those extremely small grid spaces (Figure 4-3), where they are

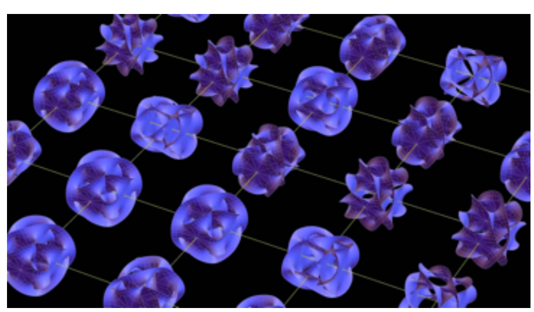

Figure 4-3. The fabric of space in M theory. Grid points in 3-dimensional space are access points to multi-dimensional shapes (Calabi-Yau manifolds) to which vibrating strings of energy are tethered.

hypothesized to form multi-dimensional shapes called *branes*[21]. That's what the vibrating strings of energy are thought to attach to. The shape of the brane determines the allowable frequencies at which the attached strings of energy can vibrate.

Moses: How many hidden dimensions are we talking about?

Socrates: In superstring theory, there are six hidden dimensions. That means that together with the usual three extended space dimensions that we experience directly plus time, our universe has a total of ten dimensions.

Moses: What about M theory? How is that different from superstring theory?

Socrates: It turns out that five separate versions of superstring theory are required to account for all of the different classes of subatomic particles in the Standard Model. Then in 1995, Edward[22] showed that if he added one more hidden dimension, all five superstring theories could be derived as limiting cases of an even grander theory that he called M theory. According to M theory, the universe has a total of eleven dimensions - three extended space dimensions, seven compactified hidden dimensions and time.

Moses: What does the 'M' stand for?

Socrates: Edward didn't say. Some suggestions have been 'Mother,' 'Master', 'Magic,' 'Mystery,' 'Membrane', so you can take your pick. Personally, I prefer 'Mother Theory', in honor of Mother Nature.

Moses: Is there any experimental evidence that these hidden dimensions actually exist?

Socrates: Not yet. Up to now, no one's been able to devise a feasible experiment capable of detecting them. The best guess is that it would require an *extremely* high energy collision in a particle accelerator, enough to transfer some of the energy released by the collision into the hidden dimensions. The idea is that since energy can neither be created nor destroyed according to the First Law of Thermodynamics, then if the total energy of the particles measured after the collision ends up being less than the total energy just before the collision, the lost energy must have been absorbed by the hidden dimensions. At the present time, however, the most powerful particle accelerators still aren't powerful enough.

Moses: But if the accelerators someday become powerful enough to validate M theory experimentally, then it's possible that the theory could not only account for all of the known subatomic particles and their quantum states, but also could provide a quantum theory of gravity that would unify it with the other two forces of nature?

Socrates: That's what some physicists currently believe. By reconciling the forces that act over the shortest distances (the strong nuclear force), intermediate distances (the

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[21] The multidimensional shapes are hypothesized to correspond to **Calabi-Yau shapes**, a type of manifold used in algebraic geometry.

[22] **Edward Witten** (b. 1951) is an American theoretical physicist and professor of mathematical physics at the Institute for Advanced Study at Princeton University.

electroweak force) and longest distances (gravity), it creates a theory that potentially explains everything from the smallest to the largest aspects of the universe. In other words, the long sought-after Holy Grail of physics, a Theory of Everything!

Moses: Would it also resolve the "God doesn't play dice" issue that bothered Albert so much?

Socrates: Unfortunately, that's a separate issue. As long as you can't predict exactly which quantum state a subatomic particle will chose when its wave function collapses, you can't know how the universe will evolve. Like those electrons being fired though the two slits (Figure 4-1). If the electron strikes the detector directly opposite the slit it went through, then the universe evolves one way, but if it ends up at a secondary node in the interference pattern, then the universe evolves in a different way. M theory doesn't resolve the measurement problem directly. On the other hand, the extra hidden dimensions postulated in M theory might help get around the "God doesn't play dice" issue in a different way.

Moses: How?

Socrates: One of the ways to resolve the measurement problem is called the Many World's Interpretation of quantum physics. Hugh [23] came up with the idea in the 1950s.

Moses: How does it work?

Socrates: He postulated that the entire universe is described by a single gigantic wave function that contains within it all possible realities. That way, when you make a measurement, instead of the wave function collapsing, all possible outcomes are realized.

Moses: How can that be, if there's only one universe, namely that one that we exist in?

Socrates: Maybe we're not alone and there is more than one universe – that's the Many Worlds Interpretation, that all possible alternative histories and futures of the universe actually exist. In other words, our particular universe is part of a multiverse, governed by a gigantic wave function that continually branches into all possible realities, so that the wave function never actually collapses.

Moses: You mean with new universes are being created all the time? You can't be serious. Sounds more like a Star Trek plot than a serious idea!

Socrates: Hey, it solves the "God doesn't play dice" issue, right?

Moses: Technically, maybe. But it brings up more problems than it solves. If the universe in which we are carrying on this conversation right now is really just one of many alternate universes in a so-called multiverse, then how do I know which one of me

[23] **Hugh Everett III (**1930-1982) was an American physicist who proposed the **many-worlds interpretation** of quantum mechanics in his doctoral thesis at Princeton University in 1957. In effect, this implies that the entire universe is described by a gigantic wave function that contains within it all possible realities.

is talking to which one of you right now?

Socrates: I know - it sounds extremely bizarre!

Moses: On the other hand, I guess it could explain how I am conversing with a sea lion right now! There must be an alternate universe where that can happen!

Socrates: See, there you are. I'm glad that you're warming up to the idea. Technically, at least, the uncertainty is gone. All possibilities are realized, since every possible quantum outcome corresponds to an alternate universe somewhere. Theoretically, the Many Worlds Interpretation provides a structure of reality that is fully deterministic rather than probabilistic.

Moses: But where do you fit all of these alternate universes? Is there really is another universe just around the corner in which I am not speaking to a sea lion right now?

Socrates: That's where the hidden dimensions in the superstring theories and M theory may come in handy.

Moses: Do you mean that the alternate universes are tucked away in those hidden dimensions?

Socrates: Why not? I know it's hard to imagine, but here's a simple analogy that may help. Even though you are a three-dimensional creature, you are restricted to living, for the most part, on the two-dimensional surface of the earth, right?

Moses: I suppose.

Socrates: So even though the earth is also a three-dimensional object like you, a whole world exists beneath its surface to which you have no access. In essence, you are restricted to living your life on the two-dimensional projection of a three-dimensional object. So think of your particular universe in the same way – the three space dimensions to which you have access are a projection of a higher dimensional multiverse. String theorists refer to it as the Holographic Principle [24]. What you perceive as the three dimensions of space in your universe are a holographic projection in a higher dimensional multiverse.

Moses: Still, the analogy to the earth's surface isn't very convincing. Deep down, we know that the earth's core really exists and that we could penetrate its full depth if we had the right tools. How does that jive with hidden dimensions that are supposedly smaller than a billionth of a billionth of a billionth of a billionth of an inch. How are you supposed to cram all of these alternate universes into such a tiny space?

Socrates: Think about it this way. How many points are there in a line?

Moses: An infinite number, of course.

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[24] The holographic principle is a tenet of string theories and a supposed property of quantum gravity that states that the description of a volume of space can be thought of as encoded on a lower-dimensional boundary to the region—such as a light-like boundary like a gravitational horizon. Also see https://youtu.be/bJpIclDmi2M (Max Tegmark, Evidence for Parallel Universes)

Socrates: And how many lines can you fit on a two-dimensional surface?

Moses: Also an infinite number, since one dimensional lines have no thickness.

Socrates: Correct again. And how many two-dimensional surfaces can you fit in a three-dimensional solid object, like a sphere?

Moses: Infinite again.

Socrates: And so forth. That means that you could cram an infinite number of three-dimensional objects into a four-dimensional object, right?

Moses: I suppose. So are you claiming that since we live in a universe with three space dimensions, adding just one more space dimension would allow us to fit an infinite number of our universes into a multiverse with four space dimensions?

Socrates: You've got it! Not only that, if the superstring or M theories are correct, then you have 6 or 7 extra spatial dimensions in which to hide an infinity of universes with three space dimensions and one time dimension. Hard to visualize, I admit, because we can only draw pictures in a maximum of three space dimensions.

Moses: I'm not sure that really helps to make the universe, or rather the multiverse, any more comprehensible. It seems like the more we try to condense the Laws of Nature into a Theory of Everything, the more unfathomable the structure of the universe becomes, with hidden dimensions and countless alternate universes whose accessibility is at best questionable.

Socrates: I don't disagree with you - even if M Theory achieves a Theory of Everything, it makes reality so bizarre that it's impossible to understand intuitively.

Moses: To me, the cure seems worse than the disease.

Socrates: Perhaps, but it's the best that modern physics has been able to come up with so far! Not all physicists agree, of course, and it may not be the last word. But so far, M Theory with its hidden dimensions is one of the strongest candidates for the long sought-after Theory of Everything.

Moses: There is one thing about these space dimensions that puzzles me.

Socrates: What's that?

Moses: Their relationship to time. If space and time are both part of the same cosmic spacetime fabric, as Albert originally showed, then why are they so fundamentally different?

Socrates: What do you mean?

Moses: In all of the space dimensions, you can go either forward or backward. But in the time dimension, you can only go forward. Why is that?

Socrates: An excellent question. Actually there's nothing in the equations governing either quantum physics, general relativity or M Theory that prevents time from going backwards. The only reason that time can't go backwards is because of another law of nature. [25]

Moses: What's that?

Socrates: The Second Law of Thermodynamics - that entropy of the universe is always increasing.

Moses: What does entropy have to do with time only going forward?

Socrates: Everything, actually. Entropy measures the extent of disorder in a system - low entropy means highly ordered, high entropy means highly disordered. [26] Take a pack of playing cards, for instance. When you buy a new pack of cards, they are usually arranged with aces on top, then kings, then queens, and so forth, all the way to the deuces at the bottom of the deck. If you do the math, that particular highly ordered sequence of cards is one of a hundred-million-trillion-trillion-trillion-trillion-trillion (52 factorial = $\sim 10^{68}$) possible ways that a deck of fifty-two cards can be arranged. Now suppose that you shuffle the deck. The probability that you will get the original ordered sequence back is extremely low, namely one out of 10^{68} for each shuffle. So by convention, the highly ordered sequence of four aces followed by four kings followed by four queens, etc., is said to have a low entropy, since only one possible arrangement (microstate) of the individual cards can account for the statistical features of the whole deck (the macrostate). As you continue to shuffle the deck, at first you will have many two and three-of-a-kind, but eventually they also become less common as the deck becomes progressively more disordered. Maximal entropy is achieved when each card has an equal probability of being followed by any other card in the deck. That is, many

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[25] To observe which quantum state a quantum particle is in requires a measurement which collapses the Ψ function to either one quantum state or the other. That is, until the measurement is made, you don't know which quantum state the particle will choose. The Nobel laureate **Ilya Prigogine** has argued that this is the key to resolving quantum mechanics with the second law of thermodynamics, which states that the entropy (level of disorganization) of the universe increases irreversibly. That is, if all quantum events are driven by random probability of particles choosing one state or another as time moves forward, then reversing time would lead to a different set of random choices, and hence would not recreate the past. This destroys the symmetry of time – that, time running backwards would not be able to recreate the lower entropy state of the past.

[26] In the physical world, the **2nd Law of Thermodynamics** states that highly ordered energy (low entropy), such as that stored in chemical bonds, inevitably is degraded to less ordered non-useful energy (high entropy), namely heat in which molecules bounce around randomly in space. There is a direct analogy between **thermodynamics and information flow**. In information theory, the Information content of a message can also measured in terms of entropy. For example, if you write a message, the letters have to be arranged in a highly ordered sequence to convey the specific information of the message. The degree to which the letters are ordered versus randomly distributed can be quantified in terms of entropy, with a high degree of nonrandom order indicated by low entropy. If you randomly shuffle the letters, however, the information content of the message degrades, such that its entropy increases as the letters become more randomly distributed and less interpretable. In this sense, entropy can also be thought of as the number of possible microstates corresponding to the microstate of a system. Quantum information theory is a field which interprets quantum physics in terms of information theory. Its practical application has been in the development of quantum computers, which use the property of quantum entanglement (the faster than the speed of light information transfer between complementary subatomic particle-waves) to improve computational speed for certain types of problems. See **James Gleick**, *The Information: A History, A Theory, A Flood* (Random House, 2011).

possible microstates can now account for the statistical features of the macrostate. You know from experience that no matter how many times you reshuffle the deck, the chances of the deck being restored back to its original highly ordered low entropy state is infinitesimal. That's how the Second Law of Thermodynamics dictates that time can only move in the forward direction.

Moses: So the arrow of time is defined by the way a deck of cards behaves when you shuffle it?

Socrates: Not just a deck of cards, but everything in nature that consists of more than an isolated fundamental subatomic particle-wave. Being an indivisible entity, a fundamental subatomic particle-wave by itself has no internal order to reshuffle. But as soon as that sub-atomic particle-wave interacts with other subatomic particle-waves to form an atom or larger composite structures, then entropy comes into play. It's the progressive decrease in the orderliness of that structure that we, as living organisms comprised of countless interacting subatomic particle-waves, perceive as the forward movement of time. That's how the Second Law of Thermodynamics constrains time to move only in the forward direction for anything larger than an isolated subatomic particle-wave.

Moses: So the arrow of time is literally caused by the group behavior of interacting sub-atomic particle-waves?

Socrates: That's right. The arrow of time emerges from the rules by which nature permits subatomic particle-waves to interact with each other.

Moses: So then even if M theory is ultimately validated someday, it won't really be a Theory of Everything if it can't explain why time only moves forward and not in the reverse direction as well. At a minimum, you'd need the Second Law of Thermodynamics plus M Theory to explain everything.

Socrates: Very perceptive of you, Moses! I agree, physicists have been a bit optimistic in calling M theory the Theory of Everything. Even aside from the issue of experimentally validating M Theory, if a Theory of Everything can't explain why time only moves forward, then it's basically incomplete.

Moses: It all seems very weird.

Socrates: Highly nonintuitive, I agree. But why should that surprise you?

Moses: What do you mean?

Socrates: You and your senses have evolved to tackle the challenges of life on earth, dealing with things on the scale of rocks, rivers, mountains, deserts, and other living organisms. Viruses are probably the smallest direct threat that you've ever had deal with, and climate change is probably the largest. That's what is naturally intuitive to you. But your survival skills have never required you to dodge subatomic particles, or escape black holes, supernovas or big bangs. So why would you expect your human mind to have an intuitive grasp of how reality operates at those extreme scales of the universe?

Moses: I suppose that you have a point. It's just hard to imagine a universe, or multiverse, containing more than the three space dimensions. These extra hidden dimensions, not to mention alternate universes, are hard to wrap my brain around.

Socrates: Here's a suggestion. Don't think of them physically as dimensions of space. Think of them abstractly, as dimensions of information.

Moses: How does that help?

Socrates: I look at this way. At the intermediate scale that we encounter in our daily lives, the information from the usual four spacetime dimensions is good enough to optimize our ability to survive, so we haven't evolved any mechanisms to perceive and store information about the other six or seven dimensions. That's why they are hidden to us, because we've never needed to perceive them in order to survive in our everyday world. However, if we want explore beyond our immediate world, to the extremely small subatomic and extremely large cosmic scales, we need to take that additional information into account. So when you boil it down, it's really about eleven dimensions of information. One of them we intuitively perceive as having the qualities of time, a dimension in which we can only move forwards. Three of them we intuitively perceive as having the qualities of extended space, dimensions in which we can move either backwards or forward. And the other hidden dimensions are mysterious because they are not directly accessible to us through our usual senses, even though they may contain whole universes of their own. Trying to imagine their geometry in physical terms will just give you a headache. So don't even try. My advice is to think of them abstractly - as information geometry.

Moses: Information geometry?

Socrates: It's much more intuitive to think of information as having eleven dimensions than to think of physical spacetime having eleven dimensions. The important point is that as long as you have the relevant information, does it really matter whether can intuitively imagine what the hidden dimensions actually look like physically? Even if they completely defy common sense, all that really matters is whether they provide a mathematical description precise enough to allow you to make testable predictions. It's not all that different from the modern scientific view of a tree that we discussed earlier.

Moses: How is that similar?

Socrates: That our five senses can only give us a limited amount of information about the true nature of a tree We can describe a tree by its visual appearance from the way photons reflect off its surface, or its texture by running our hands over the bark and leaves, or its fragrance using our sense of smell, and so forth. Each method provides a different dimension of information about the tree. There are also countless other indirect methods for analyzing the tree's properties beyond what we can perceive directly using our five senses - by analyzing the tree chemically, genetically, histologically, physiologically, evolutionarily, ecologically, etc. For example, the DNA sequences making up the tree's genes are perfectly valid descriptors, or dimensions of information, about the tree even though they can't be seen by the naked eye. We can invent a visual image in our minds of what we suppose DNA might look like, but it's really just our imagination. It's not a physically accurate representation, anymore than our visual perception of a tree characterizes the tree's true essence, at least not the 'ideal form' that Plato was after.

Moses: I guess that makes sense. In the end, all we have are the imperfect tools of our senses to interpret reality, and our senses have been tuned by evolution to intuit only a small slice of reality sandwiched between the subatomic and cosmic scales. If we can't intuitively understand the true nature of a tree, which exists at the scale that our five senses are tuned to perceive directly, how could we possibly expect to intuitively grasp the true nature of events occurring at the subatomic and cosmic scales?

Socrates: That's basically the conclusion that Niels and his colleagues arrived at with the Copenhagen interpretation of quantum physics – although it defies our notions of common sense, as long as the mathematical equations make the correct quantitative predictions, it doesn't really matter.

Moses: I guess it's very fortunate that humans evolved the ability to reason logically. Our other five senses can always fool us, but at least logical reasoning is objective and allows us to distinguish reality from illusion, even when that reality is completely nonintuitive and defies all common sense.

Socrates: How do you mean?

Moses: I mean that if we accept that experimentally-validated logical reasoning has proven that general relativity and quantum theory are correct, then what choice do we we have but to accept that black holes really exist and God does play dice with subatomic particles? And if we prove someday that M theory is correct, we may have to accept even weirder ideas, like a multiverse with extra hidden dimensions. No matter how crazy it may seem.

CHAPTER 5: Discerning Truth from Falsehood: Logic's Limits

Socrates: I agree with you that logical reasoning is, in many ways, humanity's most impressive quality. It has given you the ability to see beyond what you can perceive with your immediate five senses. Through the power of logical reasoning combined with scientific experimentation, you can imagine a universe or multiverse with highly nonintuitive properties defying all common sense. But just because logical reasoning may bring you to the conclusion that God is playing dice with the universe doesn't mean that God is actually playing dice with the universe. It just means that using logical reasoning, the human mind can't get at whatever rules God is playing by. In other words, God didn't make you smart enough to comprehend his or her rules, at least not through logical reasoning.

Moses: I thought that we agree to leave God out of the picture.

Socrates: Fair enough. In that case, I amend my statement to "Nature didn't make human beings smart enough to comprehend the rules that nature plays by." Better?

Moses: Do you really believe that there are things about the universe that human beings will never be able to comprehend through logical reasoning and scientific experimentation, no matter how good we become at it? Why?

Socrates: Because logical reasoning has its own inherent limitations. Especially the mathematical logic that you rely on so heavily in science.

Moses: How so?

Socrates: Remember when you remarked how all of Euclidean geometry could be derived from just five axioms?

Moses: Sure.

Socrates: Well, near the turn of the twentieth century, mathematicians and logicians became curious as to how rigorous mathematics really is. In other words, is there a single set of axioms from which all of mathematics and its branches could be derived as completely self-contained rule-based systems, requiring no extraneous assumptions outside of the rules defined by their axioms? For that to be true, they came to the consensus that the Axioms would have to satisfy three criteria - *Completeness, Consistency* and *Decidability*.

Moses: Which means what, exactly?

Socrates: C*ompleteness* means that any and all statements can be proved to be either true or false. *Consistency* means that if a statement can be proved true by one valid logical argument, then it can't be proved false by a different valid argument. *Decidability* means that a method can always be devised to compute whether any statement is true or false, i.e. there can be no unprovable statements.

Moses: Do the axioms of Euclidean geometry meet those criteria?

Socrates: Almost.

Moses: What's that supposed to mean?

Socrates: Actually, that's what started the ball rolling. The ringleader of the effort was David[27], arguably the most influential mathematician of the era. He had attempted to reformulate the five axioms of Euclidean geometry to remove all references to extraneous elements not explicitly specified by the axioms themselves.

Moses: Did he succeed?

Socrates: Like I said, almost. In 1899, he had succeeded in finding a system of axioms from which all the theorems of Euclidean geometry could be derived without appealing to any assumptions about the nature of the physical world. However, his proof depended on one key assumption - that the theory of real numbers had a system of axioms that satisfied the three criteria of completeness, consistency and decidability. If that could be demonstrated, then Euclidean geometry and ultimately everything else in mathematics would fall into place – a glorious Theory of Everything for mathematics!

Moses: And no one had yet come up with a set of axioms for the Theory of Real Numbers that satisfied the necessary criteria?

Socrates: Not for all real numbers. In fact, not even for basic arithmetic, which includes just integers, addition and multiplication [28].

Moses: So what happened?

Socrates: When David couldn't solve it himself, he proposed the "Axiomatic Basis of Basic Arithmetic" as one of the ten most important unsolved problems in mathematics. He presented his top ten list at the International Congress of Mathematicians held in Paris in 1900 [29] and challenged the best minds in mathematics to solve it.

Moses: That sounds reasonable, not just for the field of mathematics, but also for the foundations of science itself. Otherwise, mathematical logic could lead to contradictions that would make interpretation of scientific experiments equivocal.

Socrates: Indeed, that's the critical issue. Imagine that scientists do someday stumble upon a set of premises for a Theory of Everything that they think represent the

[27] **David Hilbert** (1862 –1943), a German mathematician and one of the most influential and universal mathematicians of the nineteenth and early twentieth centuries. Hilbert discovered and developed a broad range of fundamental ideas in many areas. A famous example of his leadership in mathematics is his 1900 presentation of a collection of problems that set the course for much of the mathematical research of the twentieth century.

[28] In **basic arithmetic**, integers are the basic arithmetic elements; addition and multiplication are the basic arithmetic operations; and commutative, associative and distributive rules are the basic arithmetic properties.

[29] Subsequently, David Hilbert added an additional 13 problems, bringing the total to 23.

fundamental axioms upon which the universe operates. And imagine that someday they find a way around chaos, quantum uncertainty and such, as Albert hoped. Then the question is, could they really depend on logical reasoning in the form of mathematical logic to explain everything about the universe definitively and deterministically, without any contradictions or unanswerable questions?

Moses: That's certainly what most of my scientific colleagues would like to think, that just like Euclidean geometry, the universe, or multiverse if it exists, has an axiomatic basis from which everything else follows logically and can be described mathematically….. and that someday, we will discover it through science.

Socrates: An inspiring idea, I agree!

Moses: Anyhow, what was the outcome? Did David's colleagues come up with an appropriate set of fundamental axioms for basic arithmetic?

Socrates: Nope. It turned out to be much less straightforward than David hoped [30]. Initially, things looked promising. By 1910, his colleagues Alfred and Bertrand[31] thought that they had succeeded when they published their masterpiece *Principia Mathematica*. But then, out of left field, came a young German logician/mathematician from Königsberg.

Moses: Who was that?

Socrates: Kurt [32]. A year after completing his doctoral thesis at the University of Vienna in 1931, he published a proof showing that for any set of self-consistent axioms powerful enough to describe basic arithmetic, there are true statements that could not be proved from the axioms, violating the *completeness* criteria. Needless to say, he caused quite a stir when he presented his findings at the international mathematics meeting in London in 1932.

Moses: What was his proof?

Socrates: Basically, he devised a method called Gödel numbering which demonstrated that it was always possible to construct a statement in the language of the basic

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[30] See *Alan Turing: The Enigma* by Andrew Hodges, Walker & Company, 2000. p 92.

[31] **Alfred North Whitehead** (1861–1947), the English mathematician and philosopher. His most notable work is the three-volume Principia Mathematica (1910–1913), an attempt to create a logical basis for mathematics, the quintessential work of classical logic, which he wrote with former student Bertrand Russell. **Bertrand Russell** (1872 –1970), the British philosopher, logician, mathematician, historian, writer, essayist, social critic, political activist, and Nobel laureate. He is considered one of the founders of analytic philosophy and widely held to be one of the twentieth century's premier logicians.

[32] **Kurt Gödel** (1906–1978), an Austro-Hungarian-born logician, mathematician, and analytic philosopher. Considered along with Aristotle and Gottlob Frege to be one of the most significant logicians in history, Gödel had an immense effect upon scientific and philosophical thinking in the twentieth century. He published his two incompleteness theorems in 1931 when he was 25 years old, one year after finishing his doctorate at the University of Vienna. The first incompleteness theorem states that for any self-consistent recursive axiomatic system powerful enough to describe the arithmetic of the natural numbers (for example Peano arithmetic), there are true propositions about the naturals that cannot be proved from the axioms. To prove this theorem, Gödel developed a technique now known as Gödel numbering, which codes formal expressions as natural numbers.

arithmetic that referred to itself in an ambiguous way.

Moses: What's that supposed to mean?

Socrates: Ever heard of the Liar's Paradox?

Moses: Sounds familiar. What is it?

Socrates: It's attributed originally to Epimenides, the Greek philosopher from ancient Crete. He pointed out that there was a fundamental logical contradiction if he, being from Crete, declared that *"All Cretans are liars."* If he was lying, then his statement couldn't be true, and if he was telling the truth, then his statement must be a lie. That's the original Liar's Paradox. A more updated version [33] is *"This statement is false."*

Moses: Very clever for a cretin.

Socrates: It's "Cretan" not "cretin."

Moses: I was just kidding. Anyhow, why is that relevant?

Socrates: Because that's basically what Kurt showed for basic arithmetic – his Gödel numbering system outlined a method to construct a statement in the formal language of basic arithmetic that was equivalent to the *"This statement is false"* version of the Liar's Paradox. By referring to itself, the constructed statement could neither be proved true nor false without leading to a contradiction. It's called Gödel's Incompleteness Theorem, which proves that basic arithmetic, the foundation of all mathematics, can't be both complete and consistent. And if basic arithmetic can't be both complete and consistent, then neither can the other branches of mathematics whose derivation depends on basic arithmetic. Quid est demonstratum!

Moses: What about the third criteria of decidability?

Socrates: That's an even more intriguing story. The same year that Kurt published his Incompleteness Theorem, a young English mathematician, Alan[34], tackled the third criteria of decidability. Like Kurt, he possessed a very original mind, with an uncanny knack for bridging the totally abstract world of formal logic and real world problems. To tackle the decidability issue, he invented what's now called the Turing machine, an

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[33] **Epimenides of Crete** was a semi-mythical 7th or 6th century BC Greek seer and philosopher-poet. As it was later realized, the Epimenide's version of the Liar's Paradox can be resolved by adding the additional axiom "Some Cretans are liars." Assuming that the Cretan who said "All Cretans are liars" is one of the lying Cretans, the paradox is resolved. But other versions of the Liar's Paradox, such as "This statement is false," are not resolvable. It cannot be true, since it asserts that it is false. Nor can it be false since then it must be true.

[34] **Alan Turing** (1912-1954), an English mathematician, computer, scientist, logician, cryptanalyst, philosopher and theoretical biologist. Turing was highly influential in the development of theoretical computer science, providing a formalisation of the concepts of algorithm and computation with the Turing machine, which can be considered a model of a general-purpose computer. Turing is widely considered to be the father of theoretical computer science and artificial intelligence. Despite these accomplishments, he was not fully recognized in his home country during his lifetime, due to his homosexuality, and because much of his work was covered by the Official Secrets Act.

automated method to calculate whether a formal statement in basic arithmetic is true or false. He then went on to prove that for all possible Turing machines, you could always create a statement in basic arithmetic that would cause a Turing machine fail to halt – that is, get stuck in an endless loop, and therefore never be able to spit out an answer. It would just go on calculating forever, never deciding whether the answer is true or false, violating the decidability criterion. It's called Turing's Undecidability of Halting Theorem.

Moses: I guess that 1932 turned out to be a pretty depressing year for David! If it wasn't bad enough that could no one could solve what he thought was a mere housekeeping matter, Kurt and Alan actually ended up proving the opposite! Like Henri proving that the Three Body Problem has no analytical solution.

Socrates: True, it was a major disappointment to David. But, on the other hand, Alan's Turing machine had an unanticipated consequence that turned out to be quite spectacular.

Moses: How so?

Socrates: With the Turing machine, Alan had conceptually invented the modern computer! He went on to put the Turing machine concept into practice after World War II at the University of Manchester, where his team engineered one the first computers. He's now considered the conceptual father of the modern computer.

Moses: So a totally esoteric problem in formal logic, literally of interest to only a handful of logicians and mathematicians throughout the world, subsequently transformed human society through the invention of the modern computer?

Socrates: Pretty amazing, isn't it, how a completely arcane area of scholarship can change the world?

Moses: Is that the same Alan who broke the code for the Enigma Machine in World War II?

Socrates: Yes, the same person. When his studies in logic were interrupted by World War II, the British government recruited him to the Government Code and Cypher School at Bletchley Park, where they put his mathematical skills to use in code-breaking. The Enigma Machine was the device used by the Germans to generate the secret code for their military operations, including positioning their U-boat submarine fleets in the North Atlantic. The code was widely considered unbreakable, but Alan's team figured it out. Once the code was broken, supply ships in the North Atlantic were able to avoid the German U-boat fleet, saving Britain from almost certain defeat.

Moses: So the same fellow who invented the modern computer also probably saved the world from Nazi domination?

Socrates: Yes, and those weren't his only contributions. After the war, he became very interested in biology and developed a mathematical theory to explain how chemical reactions can spontaneously lead to pattern formation. They are now called Turing patterns in his honor, and explain many natural phenomena, including how the stripes on a tiger or spots on a leopard form, patterns of leaf formation along the stem of a plant, and so forth. It became the foundation for an entire field of theoretical developmental biology explaining how embryos develop organs, arms, legs and other structural features from a single fertilized egg.

Moses: Wow, a very impressive mind indeed!

Socrates: Yes, one of the greatest of the twentieth century. However, he was also a tragic figure.

Moses: How?

Socrates: As a gay man who didn't conceal his sexual orientation, he was arrested in 1952 for committing "indecent acts" and sentenced to a course of estrogen injections in lieu of going to jail. He committed suicide a few years later, at the tender young age of forty-two. At least that's the official story - there's also a conspiracy theory that he was assassinated by the British Secret Service because his homosexuality was considered a security risk.

Moses: Maybe if he'd lived a longer life, he could have helped us resolve the "Man is the measure of all things" issue. Because as it stands right now, we've encountered some serious roadblocks towards achieving a complete understanding of the innermost workings of the universe through science. First chaos makes it impossible to achieve absolute accuracy in calculations. Quantum uncertainty makes everything ultimately operate on probabilities instead of certainties. The latest Theory of Everything postulates hidden dimensions and alternate universes that we have no access to. And now, to top it off, basic arithmetic and the rest of mathematics is flawed by not meeting the consistency, completeness and decidability criteria.

Socrates: That about sums it up, I'm afraid.

Moses: What is it about basic arithmetic that causes the problem? Does anyone know?

Socrates: Of course. The culprit is multiplication. If you leave out multiplication, Gödel's Incompleteness Theorem and Turing's Undecidability of Halting Theorem no longer apply [35].

Moses: Why is multiplication so problematic?

Socrates: "Force never moves in a straight line, but always in a curve vast as the universe, and therefore eventually returns whence it issued forth, but upon a higher arc, for the universe has progressed since it started."

Moses: What's that supposed to mean?

Socrates: It's a passage from the Kabbalah. It's always been one of my favorites.

Moses: Very poetic, but what does it have to do with my question?

[35] **Presburger arithmetic** is arithmetic without multiplication (addition only), and has, in addition to the logical symbols 'and', 'not', and 'there exists', the additional primitive operations '+', '=' and "0", and axioms to define these, like "x+0=x." It is both complete (in the sense of Gödel, that is every statement is either provable or disprovable) and decidable (in the sense of Turing, that is there an algorithm to tell you which).

Socrates: Ancient wisdom, within which lies the answer you seek. Think of it this way. If all you have are addition and/or subtraction to work with, then the only equations that you can write are for straight lines and flat surfaces. But once you include multiplication or other nonlinear functions[36] in your mathematics, then you can write equations for curves.

Moses: So what?

Socrates: Straight lines can only intersect at a single point. But curves can intersect at many points.

Moses: Why does that matter?

Socrates: Because when scientists want to describe a physical process in nature mathematically, they write down a set of equations known as differential equations that describe how that process's essential properties, called state variables, change over time. If you know the initial values of all the state variables and how they will change over time, then you can calculate how the process will evolve in the future. That's what really got the Scientific Revolution started, when Sir Isaac co-invented differential equations and used them to predict the planetary orbits.

Moses: What does that have to do with lines and curves intersecting, though?

Socrates: That's how you solve differential equations. If you set the rates of change of all the state variables to zero, so that none of them are changing, what would you call that?

Moses: I suppose that if nothing is changing, then the process has achieved equilibrium.

Socrates: Exactly. Mathematically, each state variable has its own "equilibrium," obtained by setting its differential equation equal to zero and plotting the resulting line or curve, which is called its nullcline. The equilibrium states for the whole process then correspond to the points where the nullclines of all of the state variables intersect (Figure 5-1).

Moses: Does that mean that when the differential equations are all linear, the process can have only one equilibrium

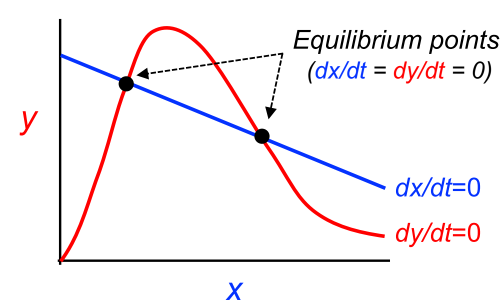

Figure 5-1. Equilibrium points. For a process controlled by 2 state variables, *x* and *y,* the graph shows a blue line corresponding to the values of *x* and y at which x is not changing (i.e. *dx/dt*=0) and a red curve corresponding to the values of x and *y* at which *y* is not changing (*dy/dt*=0). These intersect at two equilibrium points (black circles), where neither *x* nor *y* is changing (*dx/dt=dy/dt=0*).

[36] Examples of other nonlinear operations include trigonometric functions (like sine, cosine, tangent), logarithmic functions, and exponential functions

state, since equations for straight lines only intersect at one point?

Socrates: Correct. And that's pretty limiting, since many processes in nature exhibit more than one equilibrium behavior. Take water, for example – it can exist as a solid, liquid or gas – all different steady state equilibrium behaviors depending on the temperature and pressure. Or take a living organism where biological switches have to turn on and turn off processes to regulate biological function, like cell division, growth, hormone release or inflammation.

Moses: I see what you mean.

Socrates: That's why your mathematics needs multiplication and other nonlinear functions. Mathematically, it allows you to describe processes that can change from one type of equilibrium behavior to another.

Moses: That seems paradoxical. If equilibrium is defined as a steady state where nothing is changing, then once some process reaches an equilibrium state, wouldn't it be stuck there forever? How can it get to a new equilibrium state if nothing is changing?

Socrates: Very astute question, Moses! It's true that some equilibrium states are quite stable, such as a ball at the bottom of a valley that will roll back to the same position if you displace it. But equilibrium states can also be unstable, such as a ball perched at the top of a hill that will roll downhill with a slight push in any direction. In fact, most processes in nature are not at equilibrium – rather they are in a constant state of motion that is strongly influenced by the equilibrium points nearest to them. For example, the ball balanced at the top of the hill is not completely isolated. It is inevitably interacting with other natural processes, like wind, weather, erosion, earthquakes, etc. that are constantly perturbing it from the equilibrium state to one degree or another.

Moses: I see. I suppose that if those perturbations become large enough, then they can dislodge the equilibrium.

Socrates: Exactly. Stable equilibrium points that are resistant to being dislodged by small perturbations are called attractors. They can either be straight-in attractors, such as the ball at the bottom of the valley, or spiral attractors, such as a leaf spiraling inwards towards the center of a whirlpool (Figure 5-2*a*-*b*). Unstable equilibrium points that are easily

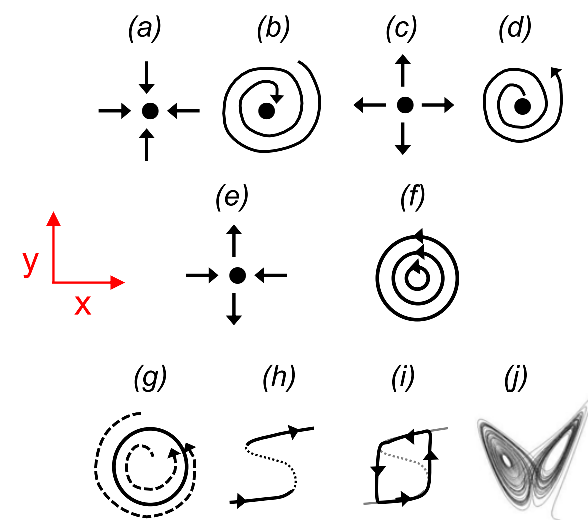

Figure 5-2. Types of equilibrium points. a) straight-in attractor; b) spiral attractor; c) straight-out repeller; d) spiral repeller; e) saddle point; f) center; g) limit cycle oscillator; h) bistablility; i) excitable element; j) strange attractor (chaos).

dislodged by small perturbations are called repellers, and likewise can be straight-out repellers, such as the ball at the top of the hill, or spiral repellers, such as an accelerating rocket spiraling outwards to reach escape velocity (Figure 5-2*c*-*d*). And some equilibrium points can be both stable and unstable at the same time.

Moses: How is that possible?

Socrates: They are called saddle points (Figure 5-2*e*). Think of a ball placed on the horn of a saddle – if you place the ball on the saddle's midline, it rolls towards the center of the seat, but if you place it off the midline, it rolls away from the center towards the stirrups. So the saddle point is stable in one direction (e.g. the *x*-axis) but unstable in another (e.g. the *y*-axis).

Moses: Anything else.

Socrates: One more - the fourth type is called a center (Figure 5-2*f*). It's in between a spiral attractor and a spiral repeller - neither stable nor unstable, but neutral.

Moses: What's that supposed to mean?

Socrates: Instead for moving towards or away from the equilibrium point, a center simply orbits the equilibrium point at a safe distance, such as the moon orbiting the earth. If it's pushed further away from the equilibrium point, the orbit's circumference increases, and if it's pushed closer in, the orbit's circumference decreases.

Moses: So six different equilibrium behaviors in all. Impressive as that is, I doubt it's enough to describe everything in nature.

Socrates: That's why you need to let multiplication and other nonlinear functions into your mathematics, so that curves can happen. With only linear equations, every process in the nature would be headed towards a single one of those six types of equilibrium states. But wherever curves intersect, there's a new equilibrium point. That allows nonlinear equations to mix and match endless combinations of straight-in and spiral attractors, straight-out and spiral repellers, saddles and centers to create a mathematical universe full of all sorts of lively new behaviors! We saw it with the logistic equation, remember (Figure 3-2)? In that equation, multiplying x and $(1-x)$ together gives you an x^2 in the product. That nonlinear x^2 term is what makes the logistic equation into the formula for a curve, namely a parabola, that generates all kinds of interesting behaviors – from a stable equilibrium to alternating patterns and even chaos (Figure 3-2). A nice example of how different types of equilibrium behaviors can emerge from even a simple nonlinear equation [37].

Moses: What "lively new behaviors" are you talking about?

Socrates: For example, if your nonlinear equations combine a spiral repeller inside a spiral attractor, the resulting behavior is called a limit cycle or oscillator, cycling endlessly around a circular trajectory called the limit cycle (Figure 5-2*g*). That's one way

[37] The **logistic equation** is an iterative map function, rather than a nonlinear differential equation.

to mathematically model the pacemaker tissue that makes your heart beat or the clock that tells your cell when to divide.

Moses: How is that different from a center?

Socrates: Because if you push the object orbiting a center further away or closer to the rotation point, the orbit changes to the new position. But if you perturb a limit cycle, the object spirals back to the same orbit. In other words, the orbit returns to the same trajectory after the perturbation, making the limit cycle oscillator like a clock that always maintains the same frequency.

Moses: What else?

Socrates: There's bistability, where the system suddenly jumps from one steady state equilibrium to another, like a switch being thrown (Figure 5-2*h)*. And then there are excitable elements, where the system jumps to a new equilibrium state when a threshold is reached and then decays back to the original equilibrium state, such as a nerve cell firing an action potential (Figure 5-2*i)*. Finally, there are the strange attractors associated with chaotic behavior, such as the turbulent air flow in the earth's atmosphere that makes the weather so unpredictable (Figure 5-2*j)*.

Moses: So adding multiplication and nonlinear functions to mathematics really expands the spectrum of possible behaviors!

Socrates: The universe, and life in particular, couldn't exist without them! Think of them as the fundamental dynamical building blocks for everything in nature.

Moses: How so?

Socrates: In nature, every process is constantly interacting with other processes in its interconnected environment, pushing and pulling each other this way and that. And if the push is large enough to propel a process into the sphere of influence of a different equilibrium state, the behavior will change accordingly [38]. So you have a whole spectrum of possible equilibrium behaviors for nature to choose between, from straight-in attractors, spiral attractors, straight-out repellers, spiral attractors, saddles, centers, limit cycle oscillators, bistable switches, excitable elements to chaotic attractors. With each process exhibiting one, several or even all ten of those behaviors under the varying conditions, the number of possible combinations is virtually endless.

Moses: I see what you mean. It sounds like you could wire them together to get any kind of behavior you want.

Socrates: In fact, that's exactly the way that I think about it. Those different types of equilibrium behaviors are the fundamental building blocks for everything in nature just like resistors, capacitors, transistors and voltage and current sources are the

[38] Equilibrium states have "**basins of attraction**" that define the boundaries between one type of equilibrium behavior and another. If the perturbation is large enough to cross a boundary, the process will transition from its current type of equilibrium behavior to the new type.

fundamental building blocks for everything in electronics. Wire the circuit one way and you get a toaster. Wire it a different way and you get a television!

Moses: It makes we wish I had a deeper understanding of mathematics. Too bad math is such an esoteric subject.

Socrates: A very common sentiment, so you're in good company. But I'll tell you what - let's go step by step to see what we need to create a mathematical universe capable of describing the real universe. We can start with basic arithmetic and build it from the ground up. What do you say?

Moses: From the ground up?

Socrates: Don't worry, it's actually fairly intuitive. Basic arithmetic gives us zero and positive integers such as one, two, three and so forth, as well as addition and multiplication. If we want to design our mathematics to represent the universe, then we need to expand from integers to all real numbers, so that we can represent portions of objects. And not just positive real numbers, but also negative real numbers, which are interesting in their own right.

Moses: How so?

Socrates: Think about what a negative number really means. In the physical world, if you have five coins, and take away three of them, then you are left with two coins, i.e. five minus three equals two. But if you only have five coins, you can't take away six coins, can you? So as far as numbering physical objects, negative numbers have no tangible meaning. Even as late as the sixteenth century, mathematicians debated the meaning of negative numbers.

Moses: So why do we need negative numbers then?

Socrates: We don't need them to represent physical objects themselves, but they are very useful for representing interactions between physical objects, like the directions in which objects move. For example, take a transaction where I lend you five coins. The coins have moved from me to you, so from your perspective, you have gained five coins, and from my perspective, I have lost five coins. If I want to express that mathematically, I can define the positive direction as movement of coins from me to you, and the negative direction as movement coins from you to me. If you then pay me back four coins, from your perspective, you now have +5-4=+1 coins. From my perspective, on the other hand, I now have -5+4=-1 coins; that is, you still owe me one coin. That's probably how arithmetic first evolved – for accounting purposes to keep track of property in early days after humans developed agriculture around ten thousand years ago.

Moses: Makes sense. I suppose that positive and negative could also indicate whether an object is moving towards you or away from you, or whether two objects are attracting or repelling each other. That could be a way to distinguish between attractors or repellers, don't you think?

Socrates: Very good, Moses, that's exactly correct! I won't go into the fine details, but different ways in which a system returns to or moves away from those equilibrium points that we just discussed (Figure 5-2) are described by what are called the *eigenvalues* of the equilibrium point. Eigenvalues can be positive or negative numbers, and the sign tells you a lot. A positive number means the equilibrium point is unstable, such that the equilibrium point acts as a repeller – like the ball at the top of the hill that when nudged rolls away downhill, or two protons whose positive charges push them apart. A negative number, on the other hand, means that the equilibrium point is stable and acts as an attractor - like a ball at the bottom of the valley that when pushed rolls back to the same place, or a proton and an electron whose opposite charges attract each other. In that way, the *eigenvalues* mathematically relate positive and negative numbers to the behaviors of physical objects in the real world.

Moses: Fascinating. What about the spiral attractors and repellers, though? How do eigenvalues being positive or negative distinguish straight-in attractors and straight-out repellers from their spiral counterparts (Figure 5-2)?

Socrates: Very astute of you, Moses. For that, we need to add another feature to our mathematics.

Moses: What's that?

Socrates: Let me illustrate by asking you a simple question. You can multiply a number by itself, correct?

Moses: Of course.

Socrates: And every positive number can be expressed as the product of two positive equal numbers, or, alternatively, two negative equal numbers, correct?

Moses: Sure, that's the square root of the number.

Socrates: But according to the rule of multiplication, no number multiplied by itself can give you a negative number.

Moses: Yes, also true.

Socrates: Doesn't that seem to violate the *completeness* criteria, since the square root and the number -1 are both is well-defined, but "What is the square root of -1?" has no answer?

Moses: I suppose. Does it really matter, though, since we were forced to give up the *completeness, consistency* and *decidability* criteria a while ago, once we included multiplication in basic arithmetic?

Socrates: Even so, how might you get around it?

Moses: I suppose we could just invent one more number, the square root of -1.

Socrates: Precisely. If we define i as $\sqrt{-1}$, such that $i^2 = -1$, then multiplying any of the usual real numbers by i generates a whole corresponding set of imaginary numbers. For example, if you want to know the square root of -4, it's just $2i$ or $-2i$. Rafael came up with the idea in 1572 [39]. It didn't get much attention at first. In fact, well into the seventeenth century, most mathematicians considered imaginary numbers to be a fictitious curiosity of no real world significance – even some of the world's greatest mathematicians, like René, disparaged them.

Moses: What happened to them?

Socrates: As it turned out, imaginary numbers were found to play a key role in the eigenvalues of equilibrium points, among other things. Generally speaking, when you solve a set of differential equations to determine their equilibrium points, the eigenvalues have both a real number component and an imaginary number component. That is, they are complex numbers.

Moses: You mean like the quadratic equation for solving polynomial equations like $ax^2 + bx + c = 0$ that I learned high school algebra?

Socrates: Exactly. The quadratic equation is $x = \frac{-b \pm \sqrt{b^2-4ac}}{2a}$, and when the term $(b^2 - 4ac)$ under the square root sign is negative, then its solution is a complex number with both real and imaginary components.

Moses: And how exactly does the eigenvalue being a complex number affect the type of equilibrium point?

Socrates: When an eigenvalue is a complex number, the sign of the real number component tells you whether object moves towards or away from the equilibrium point (Figure 5-2). If it's negative, the equilibrium point is an attractor, and if it's positive, the equilibrium point is a repeller, like we already said. The imaginary component tells you about the trajectory. If there is no imaginary component, then the object moves straight in or straight out from the equilibrium point. But if there is an imaginary component, then the object doesn't move in a straight line – it either spirals inward towards the equilibrium point as a spiral attractor, or spirals outward away from the equilibrium point as a spiral repeller.

Moses: What if the eigenvalue is a pure imaginary number with no real component? Is that a center, like the earth orbiting the sun?

Socrates: Correct. When the real number part of the eigenvalue is zero, attraction and repulsion are balanced, so the average distance between the earth and sun remains constant from one rotation to the next. The nonzero imaginary part of the eigenvalue, however, tells you mathematically that the earth is orbiting the sun, rather than standing still in relation to the sun.

Moses: Wow! So we arbitrarily add a new imaginary number *i* into our arithmetic, seemingly just to make the arithmetic more consistent and complete, and it fortuitously

[39] **Rafael Bombelli** (1526-1572), the Italian mathematician. At the time, imaginary numbers were regarded by some as fictitious or useless, much as zero and the negative numbers. Many other mathematicians were slow to adopt the use of imaginary numbers, including the French mathematician **Rene Descartes** (1596-1650) who wrote about them in his La Géométrie in 1637, where the term was meant to be derogatory.

turns out to have a profound relevance to the Laws of Motion governing our solar system. I guess that Raphael was right - imaginary numbers were not such a crazy idea after all!

Socrates: Indeed. In the 1700s, Leonhard [40] went on to prove that imaginary numbers are mathematically related to trigonometric and logarithmic functions through Euler's Formula, cementing the link between imaginary numbers and orbits. After that, no one complained that imaginary numbers were irrelevant.

Moses: It's almost like mathematical ideas are not just abstract theoretical concepts, but are actually embedded in nature, just waiting to be discovered!

Socrates: That certainly fits with the idea that logical reasoning evolved as a sense, just like sight or hearing, don't you think? In other words, our brains 'sense' mathematical ideas from the way things in nature behave, just like our brains sense the image of a tree from the photons reflecting off it and colliding with our retina.

Moses: I imagine that Plato would probably have liked that idea, that mathematical concepts are 'ideal forms' that can be sensed by the enlightened philosopher to understand the real world.

Socrates: Except Plato believed that the ideal forms represented perfection and their real world counterparts were merely imperfect realizations.

Moses: True. But even if mathematical logic has imperfections, does it really matter to science? Kurt had to go to a lot trouble to construct a basic arithmetic statement that was unprovable, whereas there are countless mathematical statements that are unequivocally true. Maybe those troublesome unprovable paradoxes are so rare that they really aren't relevant to science.

Socrates: It's not just unprovable mathematical paradoxes that are problematic. There are also the many mathematical statements that have more than one correct answer. In that case, how do you decide which answer is correct when you try to apply mathematics to the real world?

Moses: Like what?

Socrates: Have you heard the story about the journalist and the scholarly rabbi?

Moses: Sounds like you're going to tell a joke.

Socrates: Actually, it's an interview that I heard on public radio one day. The journalist was interviewing a rabbinical scholar about his newly published translation of the Talmud. The journalist remarked that one thing about the Talmud had always puzzled him. Whenever some troubling real life situation was presented to a group of learned rabbis, each rabbi in succession offered his own advice on the best approach. But at the end, there was no attempt to reach a general consensus. The reader was left with a

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[40] **Leonhard Euler** (1707-1783). Euler showed that imaginary numbers are directly related to trigonometric functions and logarithmic functions by proving that for any angle θ, $e^{i\theta} = \sin\theta + i\cos\theta$.

range of opinions to choose from, without any specific recommendation as to the best answer.

Moses: What was the rabbinical scholar's response?

Socrates: After reflecting for a moment, he asked the journalist:

"*Tell me, did you study mathematics in school?"*

"Yes, of course" replied the journalist.

"Then perhaps you can answer a simple question? What is the square root of four?"

"Why two, of course," the journalist answered.

"Ah, yes, but the square root of four is also minus two, is it not?

"Yes, I guess that's also correct," the journalist acknowledged.

"So you see," said the rabbinical scholar, *"even for a question as simple as the square root of four, there is more than one correct answer. And certainly life is much more complicated than such a simple question. So do you really expect to find a single correct answer to life's important questions?"*

Moses: I guess that it is kind of silly to imagine that questions like "What is the meaning of life?" or "What is the meaning of the universe?" could have a single answer.

Socrates: That idea has been poked fun at before. Remember the *Hitchhikers Guide to the Galaxy*[41]?

Moses: The science fiction spoof on British radio?

Socrates: Exactly. The premise was that a race of pan-dimensional hyperintelligent beings had built a supercomputer called Deep Thought to calculate "the answer to the ultimate question of life, the universe and everything." After years of calculating, Deep Thought finally revealed the anxiously awaited answer – it was the number forty-two. Needless to say, the beings were completely stymied. Deep Thought then explained that the answer was incomprehensible because they didn't know exactly what they were asking. The supercomputer then recommended that they build an even more

[41] As described in Wikipedia, **the Hitchhikers Guide to the Galaxy** relates the story of a race of hyper-intelligent pan-dimensional beings who built a computer named Deep Thought to calculate the Answer to the Ultimate Question of Life, the Universe, and Everything. When the answer was revealed to be 42, Deep Thought explained that the answer was incomprehensible because the beings didn't know what they were asking. It went on to predict that another computer, more powerful than itself would be made and designed by it to calculate the question for the answer. (Later on, referencing this, Adams would create the 42 Puzzle, a puzzle which could be approached in multiple ways, all yielding the answer 42. The computer, often mistaken for a planet (because of its size and use of biological components), was the earth, and was destroyed by Vogons to make way for a hyperspatial express route, five minutes before the conclusion of its 10-million-year program. Two of a race of hyper-intelligent pan-dimensional beings who commissioned the earth in the first place, disguise themselves as Trillian's mice, and want to dissect Arthur's brain to help reconstruct the question, since he was part of the earth's matrix moments before it was destroyed, and so he is likely to have part of the question buried in his brain. Trillian is also human but had left earth six months previously with Zaphod Beeblebrox, President of the Galaxy. The protagonists escape, setting course for "The Restaurant at the End of the Universe". The mice, in Arthur's absence, create a phony question since it is too troublesome for them to wait 10 million years again just to cash in on a lucrative deal.

powerful computer to determine the precise question for which forty-two was the answer!

Moses: Very amusing.

Socrates: The point is, once nonlinearity is mixed in, a lot of mathematical questions have more than one correct answer, such as the square root of four. Or you may have questions with no exact answer, like the Three Body Problem. In fact, unlike linear equations, most nonlinear equations can't be solved analytically at all, that is, by a pencil and paper proof. Sir Isaac was lucky with the Two Body Problem – those particular equations can be solved analytically. But add one more body and you're in trouble, as Henri proved. And it's not that we're just not clever enough to find the right solution - it's that there is no exact solution.

Moses: Then what good are equations, if most of them can't be solved exactly?

Socrates: Even if nonlinear equations often can't be solved analytically, they can be solved numerically by a computer.

Moses: How?

Socrates: Sir Isaac and Gottfried[42] co-invented calculus based on the idea that any continuous curve can be approximated by connecting extremely short straight line segments together, end-to-end (Figure 5-3). Not long afterwards, Leonhard [43] took the idea one step further. He showed that you can approximate the behaviors of nonlinear equations by breaking down their curves into very short lines, and then solving the linear equations for each segment of the curve exactly. Then you just add them together, since for linear equations, the whole is always just the sum of the parts. It's called the Euler method. It's not perfect, because the straight line segments never exactly match the true curve, but you can get as close as you want by making the straight lines shorter and shorter. It would take forever by hand, but modern computers do it at lightning speed.

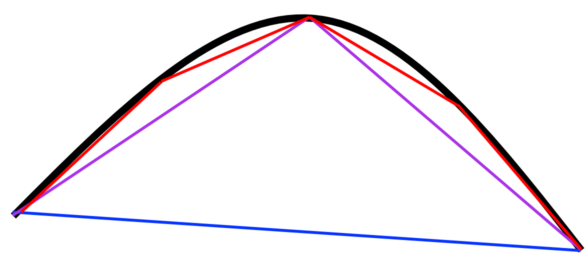

Figure 5-3. The principle of calculus. Approximating a curve with straight line segments in calculus. As the curve (black) is divided into shorter and shorter segments, straight lines drawn between the segments (from blue to purple to red, etc.) to more and more closely approximate the curve.

Moses: Very clever. Does it work for the Three Body Problem?

Socrates: It does. You can write Sir Isaac's laws of motion for each of the three planets,

[42] **Gottfried Wilhelm von Leibnitz** (1646-1716)
[43] **Leonhard Euler** (1707-1783).

which tell you how each planet's gravitational pull affects the other two planets. Then, if you know the initial conditions, that is, where all the planets are positioned in space, their masses and how fast they're moving, the differential equations of motion are like an instruction manual telling you where each planet is headed next. Even though the orbits are curved ellipses, ellipses can be approximated by very short straight line segments. So if we take very short time intervals, and assume all the planets are moving in an approximately straight lines over such miniscule time intervals, we can use the equations to calculate where the new position will be. We plug these new positions into the equations, and calculate the next time step and so forth. That's basically what the computer does to calculate planetary orbits. It's not perfect, but it's close enough for practical purposes.

Moses: So let's see if I've got it right - to solve real world problems, you need numbers to make actual measurements, along with addition and subtraction. Then to get from lines to curves, you need multiplication or other nonlinear operations like trigonometric functions, logarithms, exponents, etc. And if you add in negative and imaginary numbers to represent interactions between physical objects, you get all these interesting novel behaviors, like straight-in and spiral attractors, straight-out and spiral repellors, saddles, centers, limit cycle oscillators, bistability, excitability and chaotic strange attractors (Figure 5-2). And we can directly relate them everyday things we see in the real world!

Socrates: Well-said. But on the downside, once you include multiplication, arithmetic loses its completeness, consistency and decidability, and the solutions to most of the equations can't even be solved exactly anymore.

Moses: A lot like quantum uncertainty – if you try to measure something exactly in the real world, you can't do it – you can only get to within a certain limit of precision.

Socrates: A very apt analogy! Quantum physics has been incredibly successful in solving problems in physics, but at the cost of substituting probability for the clockwork certainty that Isaac and Albert dreamed of. However, even if such ambiguities are intellectually disappointing, it doesn't diminish the usefulness of mathematics as a tool to understand the real world. To survive in the real world, you don't need perfectly accurate calculations.

Moses: What do you mean?

Socrates: You only need calculations to be close enough to accomplish the task at hand. To jump across a ditch, it doesn't matter whether you clear the other side by an inch or a foot. Either way gets you to the other side. All you need are good enough solutions, not exact solutions.

Moses: I see what you mean. So despite its imperfections, mathematics is still a very effective survival tool.

Socrates: Yes, that's the real message! As much as we might desire perfectly accurate knowledge arising from a perfect physics and perfect mathematics, it's not achievable.

But, fortunately, it's not necessary for us to survive on this planet.

Moses: So where do we go from here? Was Siddharta right, that as far as absolute truth is concerned, logical reasoning is an illusion?

Socrates: We already knew that once we admitted that logical reasoning, whether philosophical or mathematical, is fundamentally based on axioms that are not themselves provable. If logical reasoning can never prove the truthfulness of its own axioms, then any conclusions are relative, not absolute. In that sense, logical reasoning as a path to absolute truth is an illusion.

Moses: But even if logical reasoning could get us to absolute truth, we would still need to rely on nonlinear mathematical logic to describe the universe, which leads unavoidably to unresolvable paradoxes, questions with more than one answer and questions with no exact answers at all, just like in real life.

Socrates: Very true. The important message, though, is that imperfect is not the same as useless. All of the modern technology that has transformed the human society has been derived directly from logical reasoning, imperfect though it may be. From a practical engineering standpoint, the solution to a problem doesn't have to be perfect, only good enough to achieve the goal in mind. That is all that you or I need to survive. And having many different good enough solutions gives you more flexibility and adaptability for solving life's problems, just as our sage rabbinical scholar explained about the Talmud.

Moses: OK, you've convinced me - if "Man is the measure of all things," then we are stuck in Plato's Cave with imperfect tools which can only provide good enough solutions, but not exact answers to our questions about life and the universe.

Socrates: Fairly stated, my friend, we agree!

CHAPTER 6: God Options

Socrates: Of course, if you don't want to leave the ultimate meaning of your life to an impersonal universe that you can't ever completely comprehend, you can always resort to belief in a higher power. Just because the human mind can't calculate or measure anything to absolute accuracy doesn't mean that a divine creator couldn't. It only would mean that the creator didn't make you smart enough to understand the rules. In fact, when you think about it, if an all-knowing and all-seeing higher power did create the universe, why should this higher power need any rules or Laws of Nature to keep track of what's happening in the universe? An omniscient creator would already know everything that has happened, is happening and will happen – no need for Newton's Laws, Schrödinger's equation, $e=mc^2$ or any other formulas to calculate how things are going to turn out.

Moses: I thought that we agreed to see how far we could get towards understanding the universe, life and everything else without relying on anything supernatural.

Socrates: True. On the other hand, whether you are a believer or not, belief in a divine creator has dramatically shaped the course of human civilization, so it's hard to ignore the impact. Perhaps we should consider its implications, at least from a scientific standpoint.

Moses: Fair enough. Personally, I think that humans created God to symbolize what we don't know about the universe. After all, every human culture that's ever been studied has its own creation myth. That explains why there are so many different concepts of God – each culture invents its own. If there were really one true God, then you might think that humans would have come to a more uniform consensus on what God looks and acts like. To me, God is just a figment of the human imagination.

Socrates: But if even God exists only in your imagination, then isn't that still enough to say that God exists?

Moses: If you mean that God exists as a superstitious belief in the minds of people, then I have no objection. Just like I have no objection to believing that unicorns exist as superstitious beliefs. But they're make-believe, not material physical entities.

Socrates: But things don't have to be material to be real.

Moses: Like what?

Socrates: Take language, for instance – language exists, doesn't it? And just like the various forms by which God is represented among different cultures, language also comes in many flavors - English, French, Chinese, Japanese, Arabic, Hebrew, etc. They are all products of the human mind and don't have any material physical properties like mass or energy.

Moses: But humans created language, not the other way around.

Socrates: That depends on how you look at it. Language indelibly shapes you and every other human into who you are. You are who you are because your parents, siblings, teachers, friends and fellow citizens used language to teach you how to behave as a member of society. You couldn't have become the scientist you are without language. From that perspective, language created human beings as much as humans created language.

Moses: But still, a human being had to conceive of the idea of language before the first words could be spoken.

Socrates: Depends on how you define a human being.

Moses: What do you mean?

Socrates: What makes a human different from other primates? If you consider the ability to communicate abstract ideas through language as a critical part of that definition, then a primate is not truly human until the first words that articulate abstract concepts are spoken. That is, they may be in the process of evolving towards becoming human, but they are not yet human. Call them pre-human primates or proto-humans if you like.

Moses: So you're claiming that the first real humans didn't come into existence until they spoke their first words? What about other primates? They use language, too – like vervet monkeys that have distinct calls for eagles, snakes and other dangers. And non-primates, too. I've heard that marmots even use a combination of nouns, verbs and adjectives. Many animals communicate their mood by vocalizations – growls, barks, hisses, purring, etc. Even insects like bees have their own language of sorts – the dances they do to direct their fellow bees to a food source.

Socrates: I am not denying that other animals use sounds to communicate with each other. But human language is special because it is used to convey abstract concepts, not just emotions or physical objects. As far as we know, monkeys and marmots can't discuss philosophy, the meaning of life or the existence of God with each other.

Moses: Some sea lions seem to be able to.

Socrates: Ha ha, good point! However, I'm the exception, not the rule.

Moses: Still, your argument that humans and language came into existence simultaneously is just wordplay. You're just defining things in a convenient way to support your viewpoint!

Socrates: Exactly, I couldn't agree more - it depends totally on the definitions. Here's another one. Which comes from first – the chicken or the egg?

Moses: Don't change the subject.

Socrates: Just humor me. Which comes first – the chicken or the egg?

Moses: It's a puzzle without an answer.

Socrates: Give it a try anyway.

Moses: I suppose that if you define a chicken by its phenotype - that is, whether it looks, walks and clucks like a chicken, then the chicken comes first. On the other hand, if you define a chicken by its genotype, that is, whether it contains the genes that predestine it to hatch into a bird that looks, walks and clucks like a chicken, then you could argue that the egg comes first.

Socrates: Very good. So which is it?

Moses: Like I said, it just depends on whether you choose the phenotype or the genotype as your definition.

Socrates: And from the perspective of science, which is the right choice?

Moses: It really doesn't matter which one you choose – it's arbitrary.

Socrates: So are you saying that we've discovered another question that science can't answer? "Which comes first, the chicken or the egg?" News flash! According to science, it doesn't matter! Maybe it doesn't matter to you, but it might matter to a chicken!

Moses: It's not that science can't provide an answer – science can provide a definite answer depending on which definition you choose. But a definition is, BY DEFINITION, arbitrary!

Socrates: I couldn't agree more – it all depends on the way that you define things.

Moses: You already said that.

Socrates: It bears repeating.

Moses: Why?

Socrates: Because that's how logical reasoning in science works. Premises are definitions. As our conversation has just nicely demonstrated, the conclusion that you arrive at depends on the definitions you start with, that is, the premises you chose. If your premise is that a chicken is defined by its genotype, then the egg came first, since neither of the egg's proto-chicken parents had the full complement of genes for a true chicken yet. But if your premise is that a chicken is defined by its phenotype, then you have to wait for the egg to hatch and develop before the first true chicken can come into existence. So how does science justify which one to choose?

Moses: Why does it matter?

Socrates: Just pretend that it matters. How would you, as a scientist, decide?

Moses: If it really matters, then I guess that I'd have to come up with a logical argument to justify whether the definition of the true chicken should be based on its phenotype or genotype.

Socrates: Precisely! And that logical argument justifying the correct definition of a chicken would have to be based on a set of premises. And then you would need to develop a logical argument to justify those premises in terms of an even more fundamental set of premises, and so forth, and so forth - until you eventually reach all the way back to the fundamental Axioms of the Universe.

Moses: What's wrong with that? That's how science works – its goal is to explain each set of premises in terms of a more fundamental set. Like Newton's Laws as a special case of general relativity.

Socrates: No doubt. So if you want a complete scientific explanation based on logical reasoning, then you ultimately can't stop until you've linked your premises all the way back the Axioms of the Universe underlying an ultimate Theory of Everything, like M theory or whatever it turns out to be. Until you reach that point, you can't know whether the premises upon which your conclusions are based are ultimately valid or invalid.

Moses: Point taken, but so what?

Socrates: So do you really think that the Axioms of the Universe, should you ever discover them, will tell you the correct way to define a chicken?

Moses: It does sound a bit far-fetched, I have to admit. But if you could take it that far, then I don't see why not.

Socrates: But what if you never get an answer?

Moses: Why wouldn't I get an answer eventually?

Socrates: Because it could be turn out to be like the Liar's paradox *"This statement is false."* You can't determine whether the sentence is true or false, since if it's true then it must be false, and if it's false then it must be true. The problem is that the sentence refers to itself. And if you think about it, it's the same problem with the chicken and the egg – they refer to each other, since every chicken comes from an egg and every egg comes from a chicken. The egg can't come first, because every egg comes from a chicken, and the chicken can't come first, because every chicken hatches from an egg.

Moses: As fascinating as this is, what does it have to do with God?

Socrates: Let's leave God for last, and tackle language first. Suppose you replace, "Which came first, the chicken or the egg?" with "Which came first, human beings or language?"

Moses: I guess what you're saying is that humans can't have created a language capable of expressing abstract concepts if humans already had to speak that kind of complex language in order to be considered human. And complex language can't have created humans if it didn't exist until a human spoke its first words to another human.

Socrates: Excellent. The only way out of the paradox is to acknowledge that a pre-human primate invented complex language, and when he or she first used it to communicate with other pre-human primates, then presto! - both humans and complex language came into existence at the same moment in time.

Moses: Simultaneously?

Socrates: Precisely. Now do you get now what we're really talking about?

Moses: Not really.

Socrates: Emergent properties.

Moses: Language is an emergent property?

Socrates: Of course! And so is human society. When you have a system whose components interact by positive and negative feedback, that's the formula for the whole to become greater than the sum of the parts. And that whole doesn't come into existence until the parts all come together in just the right way!

Moses: I'm still having trouble following you. How exactly does it apply here?

Socrates: The primates are the individual components, who interact with each other via language. And language can be used to promote either cooperative (attractive) or selfish (repulsive) interactions between individual primates. That feedback creates the balance of power between individuals in the society – all of your customs, morality and laws that make up human culture start from that point.

Moses: You make it sound like a simple math exercise.

Socrates: Conceptually, it is simple – it's just the details that are complicated! You begin with a group of pre-human primates, who are not yet really behaving like true humans. Then, they speak their first words to each other, and begin to communicate and interact differently. Et voilà! Suddenly, the first real human culture and the first language have all come into existence simultaneously and continue evolving from there.

Moses: This is how you explain the origins of human society?

Socrates: It's the way everything happens in nature, from large to small, cosmic to subatomic.

Moses: Everything?

Socrates: Everything in nature is a balance between attractive and repelling forces acting upon physical objects. Think of it this way. If nature contained only attractive forces, then all objects, from galaxies to subatomic particles, would be drawn together towards a single point, creating a single infinitely dense physical object, like a black hole. On the other hand, if nature contained only repelling forces, all objects would move apart from each other until they became infinitely dilute. Stable physical objects would not be able to form in space or time. So whether you're talking about galaxies or subatomic particles or anything in between, they can only form physical structures bounded in space and time if there's an appropriate balance between the repelling and the attractive forces acting on them.

Moses: That seems a bit simplistic.

Socrates: Not really. The details can get very complicated, but the principle is quite universal. Take the creation of our solar system. First, the explosion of the Big Bang sends everything flying – that's the repelling disruptive force. Then, as the universe expands and cools, the matter condenses into stars and planets due to gravity, which is the attractive cohesive force. And the balance between those opposing forces causes our particular planets to orbit around our particular sun. Up until that point, our solar system did not exist, and neither did the S, if you define the earth as the third planet orbiting our sun.

Or take a familiar earthly object, like a diamond. The individual carbon atoms interact with each other through attractive and repulsive electromagnetic forces, which keep them in an ordered lattice that forms a crystal. But a diamond doesn't exist unless the atoms, with their positive and negative charges, interact through attractive and repelling electromagnetic forces to stabilize the specific structure of the diamond. Organize the atoms using a different arrangement of the same forces and you get a lump of coal instead. Each represents a different whole that is greater than a simple sum of the parts.

Moses: Those are examples from physics and chemistry, with real material objects and real forces. In a human society, people are the real objects, but what are the forces?

Socrates: The forces are social forces, like language. Just as powerful, in their own way, as gravity or electromagnetism; they can be attractive and cohesive or repelling and disruptive.

Moses: It's an interesting metaphor, but last time I checked, nature had only three fundamental forces. Now you're adding new ones to the inventory?

Socrates: Social forces like language may not be fundamental forces, but they are derived from fundamental forces. Just like the human body is ultimately made up of different types of fundamental particles, language is a composite of fundamental forces. To speak, you use electromagnetic forces in your brain to formulate what you want to say and mechanical forces generated by various muscles to cause air flow to vibrate your vocal cords. The resulting sound vibrations are transmitted as pressure waves and cause the eardrums of the person you are speaking to vibrate, converting the pressure waves back into electromagnetic forces in his or her brain. So there's nothing supernatural about it.

Moses: It still seems like a bit of a stretch to me. The fundamental forces of nature aren't concepts, like language - they are real, transmitted by subatomic particles like photons and gravitons! How can a concept like language generate force?

Socrates: The same way that charged electrons, protons and atoms generate force – by emitting packets of energy to other charged particles. A charged particle exerts an electromagnetic force field, which either attracts or repels other charged particles by exchanging packets of energy in the form of photons. But the vacuum separating the charged particles cannot generate an electromagnetic force field - it can only transmit it. The force field itself is something that emanates from particles with charge, mass, energy, spin and other physical properties. So the charged particle and its force field form an inseparable duality. You simply can't separate the object from the force field – they are just different aspects of the same entity. Just like human society and language are an inseparable duality. Think of it this way - instead of an electromagnetic force field, people exert a language force field. And just like an electromagnetic force field causes charged particles to move one way or the other by transmitting electromagnetic force through photons, a language field causes people to move one way or the other transmitting energy via pressure waves from one person to another. Shout "Dinner is served!" and everybody comes running to the table. Shout "Who wants to wash the dishes?" and everybody runs away. Attractive and repulsive, cohesive and disruptive, just like charged particles in an electric field.

Moses: Pretty far-fetched, if you ask me.

Socrates: Actually, that's pretty much the same reaction that Sir Isaac got when he originally proposed the idea that gravity exerted a force field. Gottfried soundly mocked the idea that one body could attract another through a vacuum, with nothing directly pushing or pulling it. He thought it impossible, and even supernatural. His exact words were: "I say it could not be done without a miracle." [44] A classic example of a scientist labeling something that he didn't understand as a 'miracle', even though it's now a well-accepted scientific concept.

Moses: Okay, suppose that I give you the benefit of the doubt, and accept that humans exert a language force field that directs the behavior of other humans. How does this help us to decide whether humans created God, or God created humans?

Socrates: I think that you can look at God in the same way as language – as a social force that promotes both cohesive/attractive and disruptive/repulsive interactions between individuals in human society. If two people both devoutly believe in the same God, it's likely to bring them closer, and if they believe in different Gods, it can move them apart, to put it mildly.

Moses: So now you want to add a God force field to the language force field? I don't think my physicist friends will go for it. They're already trying to condense three fundamental forces into one, remember? That's why they're after a Theory of Everything.

Socrates: I hate to nit-pick, but if your three so-called fundamental forces all spring from a single more fundamental process, then they are not really all that fundamental – they are also composites. So language and God fields are just composites of composites. It's just like particles. An atom is not really fundamental – it is a composite of subatomic particles like electrons, protons and neutrons, which themselves are composites of even more fundamental subatomic particles like quarks. So by analogy, if you consider things that are composites of mass and energy, like molecules and cells and tissues and organisms, to be real, then how can you not consider things that exert forces on them to be real? If gravity, electroweak and strong nuclear forces are real, then composites of those forces, like language and God, must also be real.

Moses: Language maybe. I still am having trouble with the God force.

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[44] **James Gleick**, *Isaac Newton* (Vintage Books, 2003). p. 167.

Socrates: If you don't believe that a God force field can exert real effects on physical objects, just think of poor Bruno [45].

Moses: Bruno?

Socrates: One of Galileo's contemporaries, a late 16th century Dominican friar who claimed that the universe is infinite without a center and its stars were distant suns surrounded by their own planets that might support lifeforms of their own. He also rejected a number of core Catholic doctrines such as eternal damnation, the Trinity, the divinity of Christ, the virginity of Mary, and transubstantiation.

Moses: What happened to him?

Socrates: He was tried for heresy by the Roman Inquisition, found guilty and imprisoned. Then, in 1600 he was burned at the stake after repeatedly refusing to recant his beliefs. As you can appreciate, the God force field had profound physical consequences for poor Giordano. Galileo got off relatively easy by comparison.

Moses: But the Grand Inquisitor had Giordano burned at the stake, not a God force!

Socrates: Ah, but the Grand Inquisitor and his henchmen were acting in the name of God, and transmitted both energy and mass to burn Giordano at the stake in God's name. So belief in God has real physical consequences on peoples' lives, just like language. Humans use language to communicate their concept of God, but once they all come to agreement on what God represents, then God becomes a driving force in their lives that influences their behavior towards others, for better or for worse. So the effects of the God force field on human behavior are just as real as the effects of gravitational or electromagnetic force fields.

Moses: Seems like you could apply this to any concept that is communicated through language.

Socrates: Sure. Take democracy, for example. Democracy is a concept, but democracies exist as real political systems that govern human behavior. Democracy exerts a force on human behavior. It all starts with the ability to use language to communicate abstract concepts. So if you consider democracy to be real, God should be real too.

Moses: I still prefer to wait until we have solid experimental evidence that God exists.

Socrates: You are a stubborn fellow.

Moses: It's just that I still don't see a need to resort to supernatural explanations.

Socrates: Even though you don't foresee scientific reasoning providing a complete explanation of the universe?

Moses: Maybe not for the time being. But I believe that it's eventually possible, when the physicists come up with the final version of a Theory of Everything.

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[45] **Giordano Bruno** (1548 –1600), an Italian Dominican friar, philosopher, mathematician, poet, cosmological theorist, and Hermetic occultist burned at the stake for heresy in 1600.

Socrates: In other words, it's a matter of faith to you that someday this will come to pass?

Moses: Why not? It's just as valid as having faith that some supernatural diety created the universe. Besides, I don't really see how believing that the universe, life and everything else was created by an all-powerful deity makes it any easier for the human mind to grasp the complexity of nature.

Socrates: What do you mean?

Moses: Suppose, for the sake of argument, that you were this all-powerful deity who rules the universe. Think of all the details that you'd have to keep track of.

Socrates: That's why God is supposed to be all-knowing, all-seeing and all-powerful, beyond what the human mind can comprehend.

Moses: Even so, can you imagine what God's typical day ruling the universe must be like?

Socrates: You remind me of Giordano. He was fascinated by the same question. In fact, that's what got him into such trouble with the church, speculating about the infinite complexity of the universe and the challenge of managing all of the details. I remember one night, after a few too many glasses of wine, when we amused ourselves by trying to imagine Jove's to-do-list for Mercury on the coming day. As I recall, it went something like this:

> MERCURY: Jove has ordered that today at noon two of the melons in Father Franzino's melon patch will be perfectly ripe, but that they won't be picked until three days from now, when they will no longer be considered good to eat. He requests at the same month, on the jujube tree at the base of Monte Cicala in the house of Giovanni Bruno, thirty perfect jujubes will be picked, and he says that seven shall fall to earth still green, and he says that fifteen shall be eaten by worms. That Vasta, wife of Albenzio Savolino, when she means to curl the hair at her temples, shall burn fifty-seven hairs for having let the curling iron get too hot, but she won't burn her scalp and hence shall not swear when she smells the stench, but shall endure it patiently. That from the dung of her ox fifty-two dung beetles shall be born, of which fourteen shall be trampled and killed by Albenzio's foot, twenty-six shall die upside down, twenty-two shall live in a hole, eighty shall makes a pilgrim's progress around the yard, forty-two shall retire to live under the stone by the door, sixteen shall roll their ball of dung wherever they please, and the rest shall scurry at random. Laurenza, when she combs her hair, shall lose seventeen hairs and break thirteen, and of these, ten shall grow back within three days and seven shall never grow back at all. Antonio Savolino's bitch shall conceive five puppies, of which three shall live out their natural lifespan and two shall be thrown away, and of these three the first shall resemble its mother, the second shall be mongrel, and the third shall partly resemble the father and partly resemble Polidoro's dog. In that moment a cuckoo shall be heard from La Starza, cuckooing twelve times, no more and no fewer, whereupon it shall leave and fly to the ruins of Castel Cicala for eleven minutes, and then shall fly off to Scarvaita, and as for what happens next, we will see to it later. That the skirt

> Mastro Danese is cutting on his board shall come out crooked. That twelve bedbugs shall leave the slats of Costantino's bed and head toward the pillow; seven large ones, four smaller, and one middle-sized, and as for the one who shall survive until this evening's candlelight, we'll see to it. That fifteen minutes thereafter, because of the movement of her tongue, which she had passed over her palate four times, the old lady of Fiurulo shall lose the third right molar in her lower jaw, and it shall fall without blood and without pain, because that molar has been loose for seventeen months. That Ambrogio on the one hundred twelfth thrust shall finally have driven home his business with his wife, but shall not impregnate her this time, but rather another, using the sperm into which the cooked leek that he has just eaten with millet and wine sauce shall have been converted. Martinello's son is beginning to grow hair on his chest, and his voice is beginning to crack. That Paulino, when he bends over to pick up a broken needle, shall snap the red drawstring of his underpants, and if he should blaspheme for that reason, I mean for him to be punished thus: tonight his soup shall be too salty and taste of smoke, he shall fall and break his wine flask, and should he swear on that occasion, we'll see to it later. That of seven moles who set out four days ago from deep within the earth, taking different paths toward the open air, two shall reach the surface at the same time, one at high noon, and the other fifteen minutes, nineteen seconds later, and one shall emerge three yards, one foot and half an inch from the other in Anton Favaro's garden. As for the time and place, we'll see to later." [46]

Moses: Very amusing. I can see why you liked Giordano. I just hope that you're not the one who convinced him to burn at the stake instead of recanting his beliefs.

Socrates: Me, are you kidding? I always advised him to keep his opinions to himself. But he wouldn't listen - too stubborn to save his own neck! Back to the point, though, Giordano was just imagining what it would take to keep track of what happens in his small Italian village of Nola. Now expand that to the entire universe - the complexity becomes truly unfathomable.

Moses: That's exactly why it's hard to imagine that some supernatural diety, no matter how talented, could be orchestrating everything and keeping track of all those details. Much easier to ascribe the universe's evolution to Laws of Nature operating automatically, albeit in complex ways that we don't completely understand yet.

Socrates: On the other hand, the Laws of Nature have gotten pretty bizarre these days, what with curved space-time, quantum uncertainty, black holes, hidden dimensions and the multiverse. The more you peer into nature, especially at its smallest and largest scales, the more nonintuitive it becomes.

Moses: Still, a true scientist is obligated to believe whatever theory the experimental findings support, whether or not they defy intuition.

Socrates: Exactly, and a true scientist is also obligated to accept the evidence that there are limits to what science is capable and not capable of revealing. Because all the best

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46 **Giordano Bruno**, excerpt from *The Expulsion of the Triumphal Beast* (1584)

evidence so far indicates that science cannot, through logical reasoning, explain everything about the universe.

Moses: Even so, why does that mean that you should believe in some supernatural diety whose existence can't be logically proved either?

Socrates: It doesn't. Which leaves you with three options, by my reckoning.

Moses: Which are?

Socrates: Option #1. Don't believe in God. Be an atheist, who denies God's existence altogether. Or, if you want to hedge your bets, you can be an agnostic, denying God's existence until proven otherwise. Be content to know what you can through science and logical reasoning, and don't worry about the rest.

Moses: A bit like an ostrich burying its head in the sand. What's Option #2?

Socrates: Option #2 is to believe in an impersonal God. Accept that God created the universe and the Laws of Nature, and then stood back to watch – letting everything happen without intervening. You have the flexibility to be a pantheist, for whom God is really just a metaphor for the Laws of Nature. Or you can be a deist, for whom God is a creative force, life force, higher power or whatever you prefer to call it, that can be appreciated through observing nature, but is not accessible through prayer or revelation.

Moses: And Option #3?

Socrates: Option #3 is a personal God - one or as many as you like - Yahweh, the Father-Son-Holy Ghost trinity, Zeus, Bal, Thor, and so forth – God or Gods who not only created the universe and the Laws of Nature, but also actively intervene in its workings, performing miracles, listening to prayers, punishing the wicked, rewarding the virtuous and so forth.

Moses: The Old Patriarch with the flowing white hair and beard, sitting on His heavenly throne and commanding our daily lives through unseen forces? No thanks! I still prefer Option #1 – that logical reasoning guiding science is the ultimate path to a complete understanding of the universe, life and everything else, but that we just haven't gotten far enough along yet. After all, modern science has only been at it for a few centuries, and our knowledge about the universe, life and everything else has increased exponentially! Who knows how far it can take us?

Socrates: I have no objection to Option #1 – as long as you concede that your belief is FAITH-based - based on your FAITH that somehow science, using logical reasoning, will someday overcome the limitations we've discussed and eventually lead to perfect knowledge.

So far, however, the facts are not encouraging. Even if you could come up with a new type of mathematical logic that's complete, consistent and decidable, you still have to get around quantum uncertainty, which makes it impossible to predict anything exactly from the laws of physics. Second, it's not like you'll just be slightly off the mark. Because of chaos, even tiny uncertainties can get amplified exponentially, with potentially huge consequences - like the Three Body Problem and the possibility that the earth really could suddenly go flying out of the solar system some day! And third, if M-theory and the multiverse ideas are right, you'll have to deal with those bizarre extra hidden dimensions and alternate universes being created all the time!

Moses: I think you're setting the bar too high. Just because we can't predict everything that's going to happen from natural laws doesn't mean that we don't understand how the universe works. It just says that the universe is not completely deterministic from our perspective. If I just accept that randomness is a part of nature, then it's true that I lose the ability to predict things perfectly, but that doesn't mean that I don't understand the fundamental principles and Laws of Nature upon which the universe operates. Seems more logical to just accept randomness as an unavoidable fact of our existence, rather than fantasizing about supernatural forces at work.

Socrates: So instead of God playing dice, nature does! Not such a bad argument – but it still doesn't get you completely home-free.

Moses: Why not?

Socrates: I haven't revealed my trump card yet.

Moses: What trump card?

Socrates: The one that you originally brought up! Logic requires premises.

Moses: So?

Socrates: So this - you can't create something out of nothing, neither a universe nor a logical explanation of the universe. Logical reasoning has rules – you can't derive conclusions without first having a set of premises to derive them from. So let's suppose that science does someday come up with a Theory of Everything that explains the universe, life and everything else and can be experimentally verified, whether or not the randomness problem prevents you from achieving perfect accuracy in predicting how it will evolve. Even so, this Theory of Everything still has to flow out of a fundamental set of premises, a set of Axioms of the Universe that can't be reduced anything more fundamental. Even if you eventually reach this point, a Theory of Everything still can't answer the question of how those axioms came to exist! Something had to create the Axioms of the Universe!

Moses: What if I just assume that they've existed forever, and therefore require no explanation?

Socrates: Now that seems like the ostrich burying its head in the sand! Besides, the scientific evidence is against you. According to your colleagues, the Big Bang created our universe some 14 billion years ago. So you still have to explain how the Axioms of the Universe came into being during the Big Bang, not to mention what may have existed before that if the Laws of Nature were different.

Moses: I'm not saying that the same Laws of Nature always existed forever. I'm just saying that some set of universal principles has existed forever, from which our particular universe, with its particular Laws of Nature, popped out 14 billion years ago.

Socrates: Like M-theory, you mean? Extra hidden dimensions accommodating all sorts of alternate universes, with different Laws of Nature, some compatible with life, others not. Like Stephen and Leonard imagine it [47]:

> "According to M-theory, ours is not the only universe. Instead, M-theory predicts that a great many universes were created out of nothing. Their creation does not require the intervention of some supernatural being or god. Rather, these multiple arise naturally from physical laws. They are a prediction of science. Each universe has many possible histories and many possible states at later times, that is, at times like the present, long after their creation. Most of these states will be quite unlike the universe we observe and quite unsuitable for the existence of any form of life. Only a very few would allow creatures like us to exist. Thus our presence selects out for this vast array only those universes that are compatible with our existence."

Moses: Exactly, maybe the timeless universal principles that have existed forever are the ones embodied in M theory!

Socrates: But it's still the same problem. Even if M theory can explain how our particular universe came into being, without "*the intervention of some supernatural being or god*" as Stephen and Leonard wishfully state, how did the fundamental premises of M theory that are creating all of these universes come to exist? To define them as having existed forever is just passing the buck - acknowledging that science can't provide an explanation for them – we just have to accept them without being able to derive them.

On the other hand, it fits the bill perfectly for an omniscient, omnipotent God, i.e. the Creator of All Things who created the premises underlying a Theory of Everything, whether it turns out to be M Theory or some other variation.

Moses: You are relentless, aren't you?

Socrates: I've been at this for a long time.

Moses: OK, then if I can't take Option #1 without burying my head in the sand, I'll take Option #2 ….. I'll accept that there is a mysterious creative force, heretofore known as the Creator of the Axioms of the Universe, which is ultimately unknowable. But that's all that I'm going to concede. I still believe that beyond this one exception, everything else about the universe will ultimately be knowable through logical reasoning and science, assuming that someday, as science moves forward, we will find a way around the other troublesome problems.

Socrates: It's a tall order. Like I just said, first you have to get around the quantum uncertainty that prevents you from accurately predicting future events in the universe

[47] **Stephen Hawking** and **Leonard Moldinov.** *The Grand Design.* Bantam Books, 2010.

using the laws of physics. And next you have to get around the unpredictability of chaos to know whether the earth might fly out of the solar system someday. And third, you have to deal with extra dimensions and the countless alternate universes that make up the multiverse. And then fourth, you have to discover a new mathematics that is complete, consistent and decidable.

Moses: Yes, but I still can have FAITH that someday we'll figure it all out.

Socrates: Just to be completely clear, even if you do, then you still admit that the "Creator of the Axioms of the Universe" cannot be scientifically explained through logical reasoning, correct?

Moses: I am willing to concede that one point.

Socrates: So here's a radical suggestion. In the spirit of healing the rifts between science and religion, why not accept the "Creator of the Axioms of the Universe" as a minimum definition of God?

Moses: God is a very charged word, invoking all sorts of preposterous ideas, like that Old Patriarch with flowing white hair and beard, sitting on his Throne and commanding the universe. Do you really expect me to take that seriously?

Socrates: So let me get this straight. You reject the image of the Old Patriarch sitting on a throne as totally preposterous.

Moses: Definitely.

Socrates: Yet you believe that science is on the right track, with M theory as a possible candidate for a Theory of Everything.

Moses: Yes, that seems to be the most promising direction so far.

Socrates: And you admit that the premises underlying a Theory of Everything will not themselves be explainable.

Moses: Reluctantly, yes.

Socrates: And if you accept the premises of this Theory of Everything as the Axioms of the universe, life and everything else, then you believe in everything that these axioms predict?

Moses: Yes, if logical reasoning predicts them and experiments verify the predictions, then as a scientist, I am compelled to believe them.

Socrates: No matter how bizarre those predictions seem?

Moses: Yes. I know hidden dimensions and the multiverse seems like some Star Wars fantasy, but if that's where logical reasoning leads and experiments verify, then that must be the how the universe really works.

Socrates: So you will accept these completely bizarre aspects of the universe, that defy all of your intuitive perceptions about time and space and predictability and the nature of reality. But, by comparison, the idea of the Old Patriarch sitting on a heavenly throne seems totally preposterous?

Moses: That would just be injecting superstition back into the mix. I can't perform an experiment to verify that the Old Patriarch exists, but I may someday be able to do an experiment to verify the existence of hidden dimensions and alternate universes.

Socrates: So until then, what's the harm in humans visualizing the "Creator of the Axioms of the Universe" as an Old Patriarch on a heavenly throne, or a burning bush, or That Which Has No Name, or some amorphous higher power, or any other image that helps them come to terms with the universe?

Moses: In principle, there would be no harm, if the religious fanatics would stop there. But the problem is, they don't. And that opens the door for all sorts of crazy beliefs. Like the earth being at the center of the solar system, or the universe being only 6,000 years old. And even if those beliefs are fairly harmless, what about religious fanatics who believe that they'll be rewarded with seventy-two virgins in heaven when they blow themselves up in a crowd of innocent people?

Socrates: But not all religious beliefs are crazy. You also have the Ten Commandments and the Golden Rule, right? And if you reject them as meaningless superstitions because you can't deduce them from the premises of M Theory or whatever ultimately becomes your Theory of Everything, then in the meantime, how does science provide any moral and ethical guidelines for humans to live by? I hate to remind you, but humanity's track record at using science for the benefit of humanity isn't so great. Just look at what happened when you unlocked the secrets of the nuclear power –nuclear bombs first, nuclear power plants an afterthought! And look at what science and technology are blessing us with now – climate change, deforestation, pollution!

Moses: Maybe I can't derive the Ten Commandments from the premises of M Theory, but I still can justify them scientifically.

Socrates: Okay, illuminate me.

Moses: Take society's laws against murder. If I were an evolutionary biologist, my logical reasoning would be:

<u>If</u>:

Premise 1: *A cooperative social group has a survival advantage compared to individuals fending for themselves.*

<u>and</u>:

Premise 2: *By murdering each other, individuals not only weaken the size and strength of the group, but also destroy the trust that incentivizes them to cooperate, decreasing their evolutionary fitness.*

<u>then</u>:

Conclusion: *Human societies with laws against murder gain a survival advantage that allows them to outcompete and supplant lawless societies.*

Socrates: Fair enough. But a theologian can also arrive at the same logical conclusion, with a different set of premises created by God:

If:
Premise 1: *God commands that thou shalt not murder.*
and:
Premise 2: *Humans exist to serve God's will.*
then:
Conclusion: *To serve God's will, society has a duty to punish murderers.*

Moses: But a fundamental difference is that the theologian's premises are based purely on faith, not logical reasoning!

Socrates: And the scientist's premises are not based on faith also? Where did the evolutionary biologist's two premises come from?

Moses: They are pretty self-evident, I think.

Socrates: Do you mean self-evident in the sense that the world was just created that way?

Moses: I suppose.

Socrates: But who, what, how and why was it created that way?

Moses: Nature created it that way. There are fundamental Laws of Nature that created it that way. It's better than some superstitious fantasy about the universe being created in six days by some white-haired Old Patriarch!

Socrates: You can BELIEVE whichever explanation makes the most sense to you. My point is that both sets of premises are matters of FAITH. Your evolutionary biology premises remain assumptions until they can be derived logically from a more fundamental set of premises….and those can only be proved if they are derived from an even more fundamental set of premises, and so forth, all the way back to the Axioms of the Universe, should you ever get that far. And then, at the very end, you're ultimately still stuck, since your Axioms of the Universe by definition can't be proved and have to be assumed. So in the end, you can't prove that your scientific assumptions are valid anymore than a theologian can prove the existence of God. And you also can't prove that God doesn't exist anymore than a theologian can prove that your Axioms of the Universe don't exist.

Moses: Maybe, but the sad part is that religion doesn't care about proving anything logically - it's all about believing. Religion is the antithesis of logical reasoning – it's all based on faith.

Socrates: That's just not true – religion uses logical reasoning just as much as science does!

CHAPTER 7: Faith-based versus Scientific Reasoning

Moses: How can you say that religion uses logical reasoning just as much as science does? That's ridiculous!

Socrates: Spoken like a typical scientist. But hear me out. First, tell me what you mean by logical reasoning.

Moses: Reasoning based on logic, obviously.

Socrates: Does that mean you can reason without using logic?

Moses: I don't think so.

Socrates: Then why say 'logical reasoning' instead of just 'logic or 'reasoning'?

Moses: You could, I suppose. Generically, logic and reasoning are often used interchangeably.

Socrates: But logic does have a formal definition, and it's not as broad as reasoning. Formal logic, either philosophical or mathematical, refers to a set of formal axioms and logical rule-sets from which inferences can be made. Reasoning, on the other hand, is "the art of critical thinking." In addition to formal logic, it also incorporates empirical evidence, experiments, and skepticism to establish facts, theories and truths using rules of inference.

Moses: And reasoning also comes in different forms, too, like deductive or inductive.

Socrates: Exactly. Do you know the difference?

Moses: Of course, I'm a scientist. Deductive reasoning goes from the general to the specific. Like <u>if</u> *All humans are mortal* <u>and</u> *Moses is human*, <u>then</u> *Moses is mortal*.

Socrates: And inductive reasoning?

Moses: Inductive reasoning goes in the opposite direction, from the specific to the general. Like <u>if</u> *Moses is human* <u>and</u> *Moses is mortal*, <u>then</u> *All humans are mortal*.

Socrates: And how about the validity of the conclusions? Any differences between the two?

Moses: From the examples above, it's fairly obvious that a specific conclusion from deductive reasoning is more solid than a general conclusion from inductive reasoning.

Socrates: Not just more solid. In deductive reasoning, the specific conclusion is guaranteed to be true if the premises are true, assuming the terms are clear and the logical rule-sets are followed properly. In inductive reasoning, however, that's not the case. For example, I could inductively reason that <u>if</u> *Moses likes to surf* <u>and</u> *Moses is human*, <u>then</u> *All humans like to surf*. Even though both specific premises are completely true, the general conclusion is obviously not.

Moses: Basically, what you're saying is that inductive reasoning can never absolutely prove that a general conclusion is true, only that it is likely to be true because no exceptions to its predictions have yet been observed.

Socrates: Exactly. That's why quantum theory is called a theory, rather than fact or truth. The best you can say is that so far it has met all validating experimental tests that have been thrown at and made the correct predictions. But does that mean quantum theory is the absolute last word about the true nature of reality?

Moses: I suppose that if another theory made exactly the same predictions, how could you know which is true and which is false, unless you could design an experiment that one theory predicted correctly and the other didn't?

Socrates: Exactly, that's why as important as verification is to the acceptance of a scientific theory, falsification plays an essential role for distinguishing between competing theories. As far as interpreting reality goes, the scientific method can unequivocally prove a theory to be false, but it cannot prove it absolutely true beyond all shadow of doubt.

Moses: On the other hand, neither falsification nor verification are important in religious theories and conclusions, since they are taken directly from scriptures as a matter of faith. Where does logical reasoning even come into the picture?

Socrates: It comes into the picture all the time. Take society's laws against murder, for example. Religion might use the following deductive reasoning argument:

<u>If</u>:

Premise 1: *According to the Old Testament "Whoever sheds man's blood, his blood will be shed by man, for God made man in His image (Genesis 9:6)."*

<u>and</u>:

Premise 2: *John murdered Bob.*

<u>then</u>:

Specific Conclusion: *Society should put John to death.*

Moses: That seems like a pretty trivial example.

Socrates: Perhaps, but how else can you to extrapolate from the general to the specific? There is no explicit statement in the Old Testament that says *"If John sheds Bob's blood, then John's blood will be shed by man, for God made Bob in His image."*

Moses: What if I am opposed to capital punishment? I could just as easily have reasoned the exact opposite:

<u>If</u>:

Premise 1: *According to the Ten Commandments in the Old Testament (Exodus 20:1-17), "Thou shalt not commit murder."*

<u>and</u>:

Premise 2: *John murdered Bob.*

<u>then</u>:

Specific Conclusion: *John should receive a punishment other than execution, since* *murdering John would violate the Ten Commandments.*

Socrates: That would also be consistent with the Old Testament.

Moses: But both can't be right! That's like saying that the earth revolves around the sun and the sun revolves around the earth – it's either one or the other, not both.

Socrates: We can come back to the earth and the sun later. As for John's punishment, the challenge for theologians is to reconcile the two Old Testament passages. That's where inductive reasoning comes in. For example, if you believe in capital punishment, you could reason from the specific to the general that:

<u>If</u>:

Premise 1: *According to the Old Testament: 1) "Whoever sheds man's blood, his blood will be shed by man, for God made man in His image" and 2) "Thou shalt not murder."*

<u>and</u>:

Premise 2: *The Fifth Commandment "Thou shalt not murder" is referring to individual humans, and does not apply to society collectively.*

<u>then</u>:

General Conclusion: *Society is justified in putting individual murderers to death.*

Then you toggle back to the deductive reasoning mode to conclude that <u>if</u> *Society is justified in putting murderers to death* <u>and</u> *John murdered Bob,* <u>then</u> *Society should put John to death.*

Moses: And if I don't believe in capital punishment, I could just as easily reason inductively that:

<u>If</u>:

Premise 1: *The Old Testament states both: 1) "Whoever sheds man's blood, his blood will be shed by man, for God made man in His image" and 2) "Thou shalt not murder."*

<u>and</u>:

Premise 2: *In the first statement, "shed man's blood" refers broadly to any injury causing blood loss. The second statement explicitly carves out murder as an exception.*

<u>then</u>:

General Conclusion: *"Thou shalt not murder" supercedes "Whoever sheds man's blood, his blood will be shed by man, for God made man in His image." Humans, acting either individually or collectively, are not justified in putting murderers to death.*

Socrates: Very good, Moses, you should have been a lawyer! All you need now to get John off the executioner's block is to reason deductively that <u>if</u> *Humans, acting either individually or collectively, are not justified in putting murderers to death* <u>and</u> *John murdered Bob,* <u>then</u> *Society should incarcerate John for life instead of putting him to death.* That's how religion uses both inductive and deductive reasoning synergistically to arrive at valid conclusions, just like in science (Figure 7-1).

Moses: Still, how is that getting at the truth? Depending on which Old Testament passages that you pick as your premises, you can invent countless arguments for or against capital punishment!

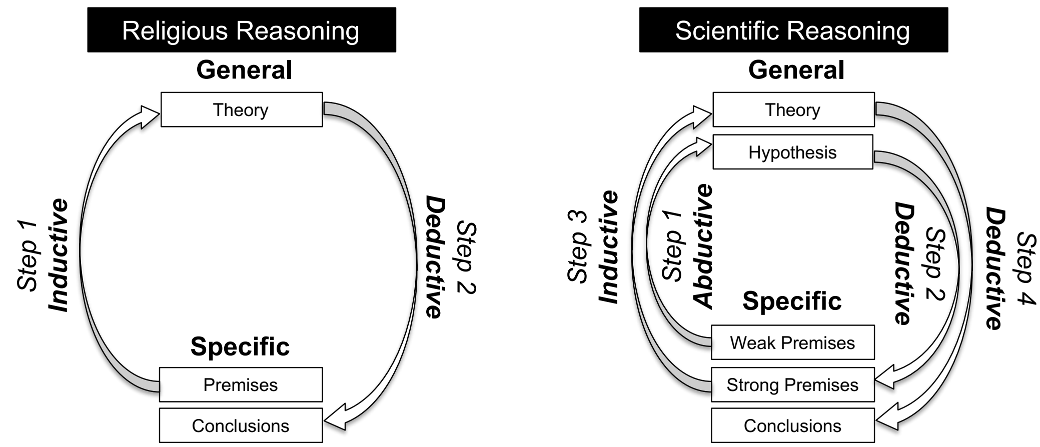

Figure 7-1. Religious reasoning: Step 1 – inductive reasoning from specific premises (e.g. scriptural passages) to general theory (religious laws); Step 2 – deductive reasoning taking general premises from religious theory to reach specific conclusions (e.g. punishment/reward of specific individuals). **Scientific reasoning:** Step 1 – abductive reasoning from specific weak premises (e.g. a few observations) to a general hypothesis; Step 2 – deductive reasoning from general hypothesis to specific conclusions/predictions (e.g. validating experiments); Step 3 – inductive reasoning from specific strong premises (e.g. many validated experiments) to a general theory; Step 4 – deductive reasoning from the general theory to specific conclusions (individual applications).

Socrates: No doubt. That's why in the Judeo-Christian-Islamic tradition, there are additional holy books like the Talmud, New Testament and Qu'ran. They are all commentaries on how to apply Old Testament passages to real life situations, as interpreted by various prophets and religious thinkers over the ages.

Moses: But how is that truth-seeking? Theologians can arbitrarily cherry pick whatever scriptural passages they wish to suit their personal sense of justice. Premises taken from scriptures are based on faith, not on observed facts or experiments, like in science.

Socrates: Do you really want a one-size-fits-all moral belief and justice system? Like the sage rabbi said, if a question as simple as the square of four has more than one correct answer, how could life's questions have only a single correct answer? That's the beauty of selecting premises from scriptures – the flexibility allows society to take into account the context in which a transgression occurs. You wouldn't want society to demand the death penalty for John if he had killed Bob in self-defense, would you? Or if he had killed Bob accidentally?

Moses: I suppose not. But if your conclusions are so flexible, how do you ensure that they are fair?

Socrates: That's always been the challenge for religion. On the other hand, when it comes to moral principles, it's even more of a challenge for science, which is intrinsically neutral on moral issues. How do you infer the Ten Commandments or the Golden Rule as logical conclusions derived from fundamental Laws of Nature? And even if you could, the Laws of Nature are derived from their own set of premises, the Axioms of the Universe, which are themselves, by definition, unprovable assumptions. In the end, you have no choice but to accept their validity as a matter of FAITH, just like the premises in religious reasoning!

Moses: Look, I admit that justifying moral beliefs like the Ten Commandments and the Golden Rule is a complicated issue for science. But there are other issues that are much more clear-cut. Take interpreting the natural world, for example. Surely you have to admit that science has the advantage over religion in that domain. I mean, just think of all the superstitious ideas about the natural world that have come from religion, like the earth being at the center of the solar system to mention just one example. For the most part, it seems to me that religious reasoning applied to the natural world yields myths, not truths like scientific reasoning.

Socrates: Technically, as long as theologians use inductive and deductive reasoning appropriately, the conclusions arising from faith-based premises are just as valid as conclusions arising from scientific premises based on natural observations. Of course, in either case, false premises give rise to false conclusions.

Moses: Exactly, that's the key issue - the validity of the premises from which the conclusions are derived! In scientific reasoning, a scientist first formulates a hypothesis based on premises derived from natural observations. The scientist then designs experiments to test whether the hypothesis is correct or not. If the new experiments don't agree, then the hypothesis is revised to be is consistent with the new results. If they agree, then the hypothesis is strengthened and eventually may reach the point where it qualifies to become a theory instead of a hypothesis (Figure 7-1).

Theologians, on the other hand, don't do hypotheses. They do God-given premises drawn from scriptures to arrive at their conclusions. Those premises are assumed to be of godly origin and therefore true, even though different scriptural passages often flatly contradict each other. That's why if it were up to theologians, we'd still be living in the Dark Ages, thinking that the sun revolves around the earth!

Socrates: Well-done, Moses, you have gotten to the heart of the matter! Scientific reasoning uses hypotheses to establish theories, where religious reasoning generally doesn't. That extra step is what separates logical reasoning in science from logical reasoning in religion. It's called abductive reasoning, and it's distinct from both deductive and inductive reasoning.

Moses: How so?

Socrates: Because unlike deductive and inductive reasoning, abductive reasoning is only weakly concerned with truth. It goes from the specific to the general, like inductive reasoning, but its goal is to formulate a general conclusion as a tentative hypothesis that requires further verification to determine whether it's true or not. Since scientists rarely get a hypothesis completely right the first time, for the most part they juggle back and forth between abductive and deductive logic, revising the hypothesis until it agrees with all of the experimental observations. At that point, inductive reasoning can then be applied to convert the now validated hypothesis into a theory.

Moses: I see.

Socrates: Here's an example. Remember when we collided surfing the same wave and I accidentally knocked you off your surfboard?

Moses: I'd rather forget it.

Socrates: I don't blame you. Sorry to bring it up. Anyway, if I took as specific premises that *Moses likes to surf* and *Moses is human*, I could use abductive reasoning to form a hypothesis that *All humans like to surf*. Now say that you have a friend named John. I could test my hypothesis with deductive reasoning, using the general premises that if *All humans like to surf* and *John is a human,* then *John likes to surf*. If it happens to be true, it would verify my hypothesis so far, and I can continue to survey other humans. At some point, I might encounter a human who doesn't like to surf. Then I would have to revise my general hypothesis to *Most humans like to surf.* If, after surveying millions of humans, I found that most did not like to surf, then I would need to further revise my general hypothesis to *Some humans like to surf.* At that point, inductive reasoning would tell me that, whereas my original hypothesis was false, my now twice-revised hypothesis has graduated to an experimentally-validated theory. It's that feedback between abductive, deductive logic and inductive reasoning that's at the essence of the scientific method (Figure 7-1).

Moses: Then that's the problem with religious reasoning - there's no abductive reasoning. Religious reasoning goes directly from God-given precepts to a full-fledged theory without any intermediate validating steps. That's a huge difference. In science, you have to be extremely lucky to get a hypothesis completely right the first time. Without feedback between abductive and deductive logic to refine a hypothesis until it agrees with all of the experimental observations, its validity as a theory remains highly questionable.

Socrates: But remember, even if a scientific hypothesis makes it through all its experimental tests to become validated as a scientific theory, a theory using inductive reasoning to reach a general conclusion can never be proven unequivocally, only confirmed repeatedly. The most that a scientific theory can do is to provide a logical explanation for a finite set of observations about nature. But in the era of modern physics, that doesn't guarantee that the theory reveals any absolute truths about nature. As Stephen and Leonard [48] have summarized it:

> "Until the advent of modern physics, it was generally thought that all knowledge of the world could be obtained through direct observation, that things are what they seem, as perceived through our senses. But the spectacular success of modern physics…..has shown that this is not the case. The naïve view of reality therefore is not compatible with modern physics. To deal with such paradoxes we

[48] **Stephen Hawking** and **Leonard Moldinov**. *The Grand Design*. Bantam Books, 2010.

> shall adopt an approach that we call model-dependent realism. It is based on the idea that our brains interpret the input from our sensory organisms by making a model of the world. When such a model is successful at explaining events, we tend to attribute to it, and to the elements and concepts that constitute it, the quality of reality or absolute truth. But there may be different ways in which one could model the same physical situation with each employing different fundamental elements and concepts. If two such physical theories or models predict the same events, one cannot be said to be more real than the other: rather we are free to use whichever is most convenient."

Moses: Even so, at least scientific theories have been validated by experimental observations. There's no validation for religious premises or theories – you are expected just to accept them as a matter of blind faith. And like we already said, logical conclusions are only as good as the premises they were deduced from!

Socrates: True. But in the end, even though religion takes its premises from scriptures, and science takes its premises from observations about the natural world, premises are still assumptions. The main difference is that scientific premises try to be more logically self-consistent with each other than religious premises. The goal in science is to derive each set of premises from a more fundamental set of premises. Like Newton's Laws being a special case of general relativity, or classical physics being a special case of modern physics. The dream is that all of science ultimately hinges on a set of irreducible premises, the so-called Axioms of the Universe, from which all other premises can be logically derived. But ultimately, the Axioms of Universe are just as arbitrary as religious axioms, because they can't be proved, and have to be assumed to be correct. And if the Axioms of the Universe happen to be wrong, then all of the premises derived from them by the scientific method are also wrong, and the whole structure falls apart. It's like a house of cards.

Religion, on the other hand, does not require its God-given premises to be logically consistent with each other, since they are based on faith, not logic. The Bible can say *"Whoever sheds man's blood, his blood will be shed by man, for God made man in His image"* in one breath and *"Thou shalt not murder"* in another. It may seem irrational that both can be true, but if the religious assumption is that the Lord works in mysterious ways that humans can't second guess, then it's not really a problem.

Moses: So the main difference is that science puts all of its premises in one basket, whereas religion spreads the risk. You're making science sound like the bigger gamble!

Socrates: In terms of getting to absolute truths about the universe, life and everything else, who can really say? Religion claims to gain that knowledge through faith, even if it's not verifiable by logical reasoning. Science, on the other, has put all its bets on logical reasoning. If science's Axioms of the Universe are wrong, then all of the derived premises fall apart. If they are right, then all of the derived premises are right. But not any more right than a different set of Axioms of the Universe that are equivalently successful at making all of the same predictions. So it's a moot point, since modern physics cannot tell you whether your latest "model-dependent reality" is absolute reality, or just one of many alternative possibilities.

Moses: In other words, nothing is certain.

Socrates: Exactly. Science is different than pure mathematics. Mathematics, despite its lack of completeness, consistency and decidability, can produce absolute certainty because its mathematical axioms are arbitrarily defined to be true. That allows you to use logical reasoning to build a mathematical structure of theorems on top of the axioms that are absolutely true. But in science, you are doing the opposite - looking at the structure of nature and trying to infer the correct axioms that explain it. In science, the inferred axioms are judged based on their empirical usefulness at explaining nature, not their absolute truthfulness.

Moses: What about Occam's Razor[49], the principle that the simplest theory explaining all of the observations is the most likely to be true? Scientific reasoning puts a lot of stock in that. As Albert famously said: *"Everything should be as simple as possible, but not simpler."* Wouldn't that help narrow down which Theory of Everything is most likely to be true?

Socrates: The key phrase is "most likely to be true." Scientists use the Occam's Razor argument to justify that the simplest explanation is the truthful one, but why should nature be as simple as possible? More likely, it's the human mind that needs simplicity to predict how nature will behave, because the human mind can only handle so much complexity. A simpler theory seems more elegant and beautiful because it's easier to comprehend and less confusing than a complicated theory. But just because the simpler theory accurately predicts observations that we make about the universe doesn't mean it represents the true nature of the universe. To prove that, you would have to show that all other models of reality, including more complicated ones, failed in some way. And since the number of possible models is infinite, that would be impossible to show.

Moses: So what you're really saying is that only way to justify the Occam's Razor principle is to claim it as one of the Axioms of the Universe, since it's basically an unproven and unprovable assumption.

Socrates: That's a good way to put it.

Moses: You're making our quest for absolute truth about the nature of the universe through scientific reasoning seem pretty hopeless.

Socrates: Take heart. Scientific theories are still very useful, even if you can't prove their validity in any absolute sense. Take Newton's Laws of Motion - even though his fundamental conceptualization of space and time as absolutes proved to be wrong from the viewpoint of modern physics, classical Newtonian physics was good enough to drive

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[49] **Occam's razor**, also referred to as the **parsimony principle**, proposes that if two explanations exist for an occurrence, the one that requires the smallest number of assumptions is usually correct. Another way of saying it is that the more assumptions you have to make, the more unlikely an explanation. The idea is always to cut out extra unnecessary bits, hence the name "razor." The term comes from a misspelling of the name William of Ockham, a brilliant medieval theologian, philosopher, and logician.

technological development for quite a few centuries! Quite an admirable example of how "model-dependent realism" changed human society forever.

Moses: Still it's pretty disappointing to think that we can never truly understand the world that we live in.

ocrates: No need to get depressed. Here's a simple suggestion: instead of arguing about whose premises are right and whose are wrong, since both are ultimately arbitrary anyway, why not work together? Convince your religious brethren that there must be a reason why God gave humans the ability to reason scientifically – so that they should use it to better understand their place in the God's universe, and to make the world a better place for all of God's creatures, whether through science or religion.

Instead of emphasizing your differences, celebrate the fact that starting from completely different perspectives and approaches, you've independently arrived at the same conclusions justifying the need for society to have laws against murder and other harmful transgressions. Doesn't that enhance your confidence that you are all on the right track, especially for complicated moral and ethical questions?

Moses: I guess that's the real goal, to arrive at better solutions to how we treat each other and the planet.

Socrates: Exactly. The important point is that if science and religion can both arrive at the same good and just solutions, does it really matter where the premises upon which they were based came from? Why should they start with the same premises when they aren't even starting with the same questions?

Moses: What do you mean?

Socrates: When you strip it down, science and religion are really asking fundamentally different questions. Science ultimately wants to know *"What are the fundamental Axioms that explain how the universe works?"* Religion ultimately wants to know *"Who or what created those Axioms of the Universe?"* So why argue? Why not focus instead on the best way to combine the best of both approaches to serve humanity, the biosphere and the planet earth? Why not, as Stephen Jay [50] suggested, treat science and religion as "non-overlapping magisteria"– that is, separate domains using different tools for meaningful discourse and resolution. Science covers the empirical realm of what the universe is made of and why it works the way it does, and religions cover questions of ultimate meaning and moral value.

Moses: That's a nice way of thinking about it. And how has that idea been received?

Socrates: Unfortunately, not very well. It didn't seem to satisfy the new atheists at any rate. Richard [51], for example, argued that the division between religion and science is not that simple, because almost all religions claim the existence of miracles, which *"by definition, violate the principles of science"*. Then he went even further, claiming that

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[50] **Steven J. Gould**. Nonoverlapping magisterial. *Natural History* 106: 16–22 (1997).
[51] **Richard Dawkins.** *The God Delusion*. First Mariner Books, 2008.

religion doesn't have anything meaningful to say about ethics and values, and therefore has no authority to claim a magisterium of its own.

Moses: That's an ironic twist, to claim that religion doesn't have anything meaningful to say about ethics and values. That's the accusation usually made about science – that Darwinian evolution justifies anything enhancing survival of the species, whether or not it conforms to moral and ethical standards.

Socrates: And you have to admit, science is certainly a long way from a scientific argument that derives the Golden Rule and the Ten Commandments from whatever the Axioms of the Universe turn out to be. If neither religion nor science has anything meaningful to say about morals and ethics, then what is left to guide you?

Moses: I see your point, but as much as it would be great to have science and religion working in harmony to solve problems collectively, there's still the obvious problem – what happens when the God-given premises and scientific premises conflict? Like the Catholic Church persecuting Galileo over his claim that the sun rotates around the earth, for instance?

Socrates: I admit that poor Galileo suffered over that one. But, in the end, the Church came around, and even apologized eventually.

Moses: Nearly four centuries later[52]?

Socrates: Better late than never!

Moses: That's the problem with religion - the faithful take their scriptures too literally! That's why are so many of the world's problems involve religious conflicts. If each religion believes its faithful followers are the chosen people doing the work of their particular God, and nonbelievers are sinners, how is that ever going to solve the world's problems? The end result of religion is warfare and genocide, not world peace!

Socrates: That's a bit harsh, don't you think? Most modern wars have been fought for secular, not religious, reasons – World War I, World War II, the Korean War, the Vietnam war, the Persian Gulf Wars, and so forth. None of those were primarily religious wars! In fact, despite all the material advances that science has generated, it has done little to tame the human taste for warfare. Mostly, it's just amplified the destructive consequences by creating more and more powerful weapons. What a waste! Like Ike warned about the military-industrial complex in the 1950s [53]:

> "Every gun that is made, every warship launched, every rocket fired signifies in the final sense a theft from those who hunger and are not fed, those who are cold and not clothed. This is a world in arms. This world in arms is not spending money alone; it is spending the sweat of its laborers, the genius of its scientists,

[52] **Pope John Paul II** issued a papal apology to Galileo in 1992.

[53] **Dwight D. Eisenhower** (1890-1964), 34th US President from 1952-1960. Excerpt is from his Chance for Peace speech (also known as the Cross of Iron speech) delivered on April 16, 1953, shortly after the death of Soviet dictator Joseph Stalin.

> the hopes of its children. This is not a way of life at all in any true sense. Under the clouds of threatening war, it is humanity hanging from a cross of iron."

Those are pretty powerful words from a military general and US president!

Moses: But science is neutral, and, as you just pointed out, can be used for good or bad purposes. The scientists are not the war-mongers – it's political leaders who start wars.

Socrates: That's like a gun lobbyist saying *"Guns don't kill people, people kill people."* Don't scientists bear any responsibility? Even if the scientists don't start the wars, they have been directly responsible for amplifying its destructive consequences to a much grander scale than ever previously possible. Even today, in the US, your scientific colleagues are busy spending twice as much money on defense research as on biomedical research[54]. Why don't scientists take the high moral ground and refuse to cooperate?

Moses: The problem is that scientists don't control how funds for science are spent – it's the politicians.

Socrates: Then don't you think that scientists would have more influence over the politicians if they joined forces with the people of faith, rather than blaming religion for all the ills of society? As long as the scientists think that religious people are ignorant and superstitious, and the religious people think that scientists are godless and amoral, what hope is there for humanity?

[54] **US defense budget** in 2016 was $600 billion annually (greater than that of all other nations combined), of which $83 billion (14%) was spent on research. The same year, **US health care** costs were $3.65 trillion annually, of which $27 billion (<1%) is spent on biomedical research.

CHAPTER 8: ReliEnce: A Novel Belief System

Moses: You make a good point. If we could get both scientists and people of faith to play on the same team, maybe we could make more progress in solving humanity's problems.

Socrates: That's exactly why I'm so thrilled that you, a formerly agnostic scientist, have finally come around to accept that God exists after all!

Moses: What are you talking about?

Socrates: You selected Option #2, remember? You professed your newly found belief in a Creator of the Axioms of the Universe, which, as I recall, was our mutually agreed upon minimum definition of God. Congratulations, Moses, you are now a believer!

Moses: Why do I feel duped?

Socrates: Nonsense. You arrived at your new religious faith purely by logical reasoning, and even established a scientific proof that God exists. Hallelujah indeed!

Moses: You've lost me. What proof?

Socrates: Very simple. You agreed that scientific reasoning has fundamental limitations that preclude it from revealing a perfect understanding of nature, or, at a minimum, how the Axioms of the Universe upon which the universe, life and everything else operate were created. In other words, a part of the universe exists that is unknowable (*U*) through science. Then you also agreed to a minimum definition of God (*G*) as that part of the universe that is unknowable through science. So here's your logical proof:

If:

Premise #1: *U exists.*

and:

Premise #2: $U = G$

then:

Conclusion: *G exists.*

Quid est demonstration!

Moses: Nice try, but before you baptize me, you need to answer one more question that's been bothering me ever since you brought up the issue about logical reasoning itself being flawed because it's not complete, consistent and decidable. How can you make an airtight argument when you've just acknowledged that your method for making the airtight argument, namely logical reasoning, is inherently flawed? Using a flawed method to prove that something is flawed seems like saying that two wrongs make a right. Don't you need a valid method to prove something beyond a shadow of a doubt?

Socrates: A clever attempt, Moses, but I'm afraid it won't get you out of your baptism. Just because formal logic contains statements that cannot be proved true or false, that doesn't mean that all statements are ambiguous. The version of the Liar's Paradox *"This sentence is false"* is ambiguous because of the way the subject of the sentence refers to itself. You simply can't determine whether the sentence is true or false, because if it's true then it must be false, but if it's false then it must be true. That's also basically what Kurt proved about basic arithmetic, on which the rest of mathematics depends. But that does not mean that the validity of ALL statements is in question. Many statements are unequivocally true, and many are unequivocally false. For example, "Moses is human" is true, but "All humans like to surf" is false; likewise, "2 + 2 = 4" is true, but "2 + 3 = 4" is false. Our proof that God exists isn't contaminated by any self-reference like the Liar's Paradox, and so is perfectly valid. Now, any other objections before I baptize you?

Moses: Just one. Do we really have to refer to the Creator of the Axioms of the Universe as "God"? It's such a charged word for scientists. Why can't we just acknowledge that the Axioms of the Universe have existed forever and leave it at that?

Socrates: Very simple. Because if the Axioms themselves are not explainable from natural laws, then, by exclusion, they must be supernatural. And if they were created supernaturally by an entity that has existed forever and from which sprang the universe, life and everything else, that sounds to me like a pretty conventional definition of God!

Moses: Look, there are things that have no beginning and no end that are not supernatural. Take a circle, for instance.

Socrates: I'm afraid that circular reasoning won't help you either! To create a circle in the real world, you have to start at a specific point in space and time. It's only after the circle has been completed that you can no longer tell where it started or ended. If you claim that the Axioms of the Universe are the basis for the universe, life and everything else, then it is a perfectly valid question to ask, what caused the Axioms of the Universe to come into existence so that our universe could come into existence?

Moses: Still, if you claim that God created the Axioms of the Universe, then it's also a valid question to ask, what created God?....and what created the creator that created God?…and what created the creator that created the creator that created God?…and so forth, *ad infinitum*. So postulating the existence of God as the creator of the axioms of a Theory of Everything doesn't really solve anything either.

Socrates: Very perceptive of you, Moses. Even Aristotle wrestled with that one. The problem is time.

Moses: What do you mean?

Socrates: As a mortal, we are trapped in the arrow of time – for us, everything in our universe has a beginning and an end. That's how you distinguish cause from effect – the cause always precedes the effect, not the other way around. For God to be the Creator of the Axioms of the Universe, God had to exist prior to the Axioms of the Universe, which themselves existed before our universe came into being. So if God is also stuck in the arrow of time, like the rest of us, it's natural to ask, 'What came before God?' There's only one way out.

Moses: What's that?

Socrates: God has to be outside of time. Then you don't need a creator that created God, and another creator that created the creator that created God, and so forth. And you get another bonus, too – if God is outside of time, then by definition, God knows everything that ever has or will happen. So it kills two birds with one stone. Not only does God not require a creator, and God is both omniscient and omnipresent.

Moses: You're saying that if God is outside of time, then God can essentially travel instantaneously through time in either direction. From God's standpoint, events wouldn't have a beginning or an end, they would just exist over an eternity that God could visit instantaneously whenever God felt like it. God would know everything about the past, present and future, since they would all be blended together.

Socrates: Correct.

Moses: There's a problem with that, though. If God exists outside of time and therefore is both omniscient and omnipresent, then how can God then be omnipotent as well? If God already knows how everything is going to turn out, then God can't really change what is going to happen. And if God can't change the future, then God isn't omnipotent. What do you say to that?

Socrates: For you personally, it's not an issue. Remember, you chose Option #2, an impersonal God who doesn't intervene in the daily workings of the universe. In that case, God just lets the universe run on its own and doesn't ever change the future. Que será, será, as they say. You are home free! Congratulations!

Moses: Not so fast. Even if that explanation works for me, it won't satisfy the Option #3 people who believe in a personal god who does intervene in our daily lives. If God already knows how the future is going to turn out, then how can God change the future to answer prayers, reward virtue or punish sin? If I, as a scientist, try to argue to religious people that, logically-speaking, their personal god cannot be omnipotent, that's definitely going to be a deal breaker.

Socrates: That's the great thing about modern physics. It's so flexible compared to classical physics.

Moses: What do you mean?

Socrates: Assuming that you accept the latest that science has to offer, like M theory and the multiverse, then you have the perfect explanation. If the multiverse really exists and the Many Worlds Interpretation is correct, then reality does contain all possible past, present and future histories of own universe plus many others. So all possible outcomes of the universe actually do exist. In other words, if God is the creator of the multiverse, then God also created all possible futures of every possible universe. By that reasoning, God's omnipotence is far greater than merely changing the future from one specific outcome to another, since God has and is continuously creating an infinite number of alternate universes corresponding to all possible pasts and futures of our universe. Now that's real Omnipotence, with a capital O!

Moses: Very clever. However, I doubt that many of my physics colleagues would see it that way. Remember what Stephen and Leonard [55] said: *"M-theory predicts that a great many universes were created out of nothing. Their creation does not require the intervention of some supernatural being or god."*

Socrates: They are entitled to their opinion, like everyone else. But ultimately, their opinion is logically flawed, since it doesn't account for how the Axioms of the Universe, from which all of these universes were *"created out of nothing,"* came into existence.

Moses: But even if M theory is correct, how can God be outside of time? Easy to say, but what is it supposed to mean? Time is such a fundamental property - how can you just eliminate it?

Socrates: I'm not eliminating time from our everyday universe. But what if the fully-realized eleven dimensional multiverse doesn't have time as one of its dimensions?

Moses: Why wouldn't the multiverse have time?

Socrates: I'm just saying that if God needs to be outside of time, and God exists in an eleven dimensional multiverse without time, then that would solve the problem.

Moses: But how can you just remove time from the multiverse? Wouldn't that violate all the known laws of physics?

Socrates: I don't know, maybe it would. But one of the intriguing about physics, both classical or modern, is that, based on the equations themselves, there is nothing that prevents time from going backward. In fact, in modern physics, some things do go backward in time, such as antimatter particles like positrons. So even though we, as mortal beings, can only go forward in time, the Laws of Nature, as currently formulated, do accommodate time going in both directions.

Moses: Even so, it's still time that you're talking about. What does that have to do with the multiverse not having time as a dimension?

Socrates: Let me ask you a question. Doesn't it seem strange that if space and time are fundamentally interwoven together into a single space-time fabric, we can only

[55] **Stephen Hawking** and **Leonard Moldinov**. *The Grand Design*. Bantam Books, 2010.

move forward in the time dimension, but we can move both forward and backward in the accessible space dimensions?

Moses: Why is it strange? Just because space and time interact with each other in space-time doesn't mean that they can't have fundamentally different properties.

Socrates: But what if space and time aren't different? What if they just appear to be different to us?

Moses: What's that supposed to mean?

Socrates: According to M theory, the multiverse contains a total of ten space dimensions and one time dimension. You have to admit, it would be simpler and more elegant for the multiverse to have eleven dimensions that are all the same, instead of one outlier that's different from the rest.

Moses: Sure, it would be simpler, but as Albert said, *"Everything should be as simple and possible, but not simpler."* I don't see how it would work, since we definitely have time in our own universe. If the multiverse doesn't include time as a separate dimension, then where did it come from in our universe?

Socrates: Maybe time is really a space dimension, but one that we, as mortal living organisms, only have partial access, so that we can go forwards but not backwards.

Moses: So you're saying that in our particular universe, we have full access to three extended space dimensions and partial access to one space dimension, which we interpret as time? Sort of a fractal universe with three and a half accessible space dimensions, where the half dimension is time[56]. And all embedded in an eleven-dimensional multiverse with seven additional hidden space dimensions?

Socrates: Exactly.

Moses: And how exactly do you get half of a space dimension?

Socrates: That's the cool part – they come from black holes.

Moses: Black holes? Like when a massive star collapses into itself?

Socrates: Exactly, so massive that the force of gravity overwhelms all of the other fundamental forces, and that no mass or energy that enters a black hole can escape.

Moses: If we were in a black hole right now, wouldn't we be ripped apart by gravity as we hurdled towards its center at faster and faster speeds?

Socrates: Probably, but I'm not talking about us being swallowed by a black hole in our own universe. I'm talking about our universe having been created when a black hole formed in a higher dimensional universe!

[56] As defined here, our universe is considered to be four dimensional space-time if time is considered to be a separate type of dimension, but 3½ dimensional if time is considered to be a partially collapsed space dimension. Likewise a five dimensional space-time universe is equivalent to a 4½ dimensional universe if time is considered to be a partially collapsed space dimension.

Moses: A higher dimensional universe?

Socrates: Exactly. A higher dimensional universe with four fully accessible space dimensions, one partially accessible space dimension serving as time, and six hidden compactified space dimensions.

Moses: And where exactly did this higher dimensional universe come from?

Socrates: From a black hole in a universe with five fully accessible space dimensions, one partially accessible space dimension as time, and five hidden compactified space dimensions. The way I see it, if we are really part of a multiverse that has eleven dimensions in all, and we exist in one of an infinite number of universes with three fully accessible space dimensions and one partially accessible space dimension as time, then maybe there are also other universes with different combinations of accessible and hidden space dimensions.

Moses: Let me get this straight. It's not already complicated enough to believe in a multiverse containing an infinite number of universes like ours. Now you want to make it even more complicated, with universes having anywhere from one to eleven fully accessible space dimensions?

Socrates: Exactly! That's how we can explain how God being outside of time!

Moses: This I can't wait to hear.

Socrates: Here's how it works. A black hole in our universe forms when a massive star collapses into itself, so massive that the force of gravity overwhelms all of the other fundamental forces. The black hole keeps shrinking into a denser and denser mass, and sucks everything else nearby into it, including light. You can enter, but you can't leave. And once you get sucked into a black hole, you just keep accelerating forever towards the singularity at its center. So far so good?

Moses: I still don't see where this is all leading, but go on.

Socrates: The key point is that before you enter a black hole, say in our universe, you are able to move both backward and forward in three space dimensions: *x, y, z*. Once you enter the black hole, however, you can presumably still move backward and forward in two of those space dimensions, *x* and *y*, but in the third space dimension, *z,* you are only allowed to move forward towards the singularity at the center of the black hole – you can't back up because there are no forces capable of overcoming the gravitational pull. In other words, one of your space dimensions has become just like time – you can only go in one direction, which is forward. A space-time inversion, as black holes have sometimes been called.

Moses: Essentially, you're claiming that if you were sucked into a black hole and survived, you'd have full access to only two space dimensions, with partial access to the third, that somehow gets incorporated into your perception of time. Sounds pretty crazy to me.

Socrates: Not totally crazy, from what we already know about black holes.

Moses: What do you mean?

Socrates: According to the theory, the entrance to a black hole, its so-called event horizon beyond which nothing that enters can escape, is a two dimensional surface. In other words, the black hole itself has no actual volume! It's an object with only two fully accessible space dimensions and time, embedded in our universe with three fully accessible space dimensions and time.

Moses: Quite spooky, when you think about, to imagine something as massive as a black hole sucking up everything nearby like a giant vacuum cleaner, yet it doesn't actually take up any volume in our universe!

Socrates: I agree. Black holes are strange beasts. And they have other strange properties that may also be relevant to our hypothesis about the nature of time.

Moses: Like what?

Socrates: It has to do with entropy. When mass or energy gets sucked into a black hole, all of the information about its quantum states should disappear, since no information can escape from a black hole. But that quantum information is a form of entropy, implying that the entropy of the universe has decreased.

Moses: Wouldn't that violate the Second Law of Thermodynamics?

Socrates: Exactly. That's why according to the theory of black hole thermodynamics, the quantum information doesn't disappear, but is left behind on surface of the black hole's event horizon. In fact, physicists have calculated that majority of the entropy in our universe is contained on the event horizon surfaces of black holes. A black hole itself contains very low entropy, since the only quantum information that we can ascertain are its total mass, spin and charge.

Moses: So if our own universe is a black hole in a higher dimensional universe, it would have started with low entropy.

Socrates: Exactly. That could solve the whole entropy paradox.

Moses: What's that?

Socrates: It goes like this. For entropy to have increased progressively ever since our universe was created by the Big Bang some fourteen billion years, then it must have started with a much lower entropy than it has now, right?

Moses: I suppose so.

Socrates: Then how did the Big Bang create a universe with such a high degree of order in the first place?

Moses: I have to admit, that's a very good question. You'd think that an explosion like the Big Bang would create a lot more disorder than order!

Socrates: But not if the Big Bang that created our universe was really due to a black hole forming in a higher dimensional universe. Then that black hole would have left all of its entropy on the surface of its event horizon. In turn, that could explain how our universe started with low entropy, which has been increasing ever since in accordance with the Second Law of Thermodynamics!

Moses: Very clever, I have to say. Now I see where you're going with this. You're saying that if there are a total of eleven space dimensions in the multiverse, and the force of gravity causes one of the space dimensions to collapse and form a black hole, that Big Bang creates a new low entropy universe with ten space dimensions in which you could move both forward and backward, and one space dimension in which you could only go forward, towards the singularity. That partially accessible half of a space dimension becomes what you perceive as the arrow of time in a universe whose initially low entropy progressively increases in accordance with the Second Law of Thermodynamics. Then, if a black hole forms in that universe and one more space dimension collapses, you would have only nine remaining fully accessible space dimensions in which you can go both forward and backwards, and one previously fully accessible space dimension in which you now can only go forwards. What happens to the eleventh dimension that used to be perceived as time?

Socrates: That dimension becomes completely inaccessible, so that you can no longer move in it at all, either forward or backwards. In other words, from your perspective in that universe, it would now be a compactified hidden dimension.

Moses: I see. And then what?

Socrates: And so it goes on, dimension by dimension. After eight space dimensions have been collapsed due to black holes forming within black holes, you get to our universe, with only three fully accessible space dimensions left, one partially accessible space dimension that we perceive as time, and seven hidden compactified space dimensions.

Moses: So we are a black hole within a black hole within a black hole, eight times in all (Figure 8-1)?

Socrates: It would be one way to explain how the multiverse generates universes with different numbers of fully accessible space dimensions.

Moses: In other words, M theory's version of "turtles all the way down" [57], only updated to "black holes all the way down!"

Socrates: Look, I know it sounds crazy. On the other hand, if you are already willing to accept the M theory's version of reality, with an infinite number of universes embedded in an eleven dimensional multiverse, how big of a stretch is it, really?

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[57] As the anecdote goes, after **William James** (1842 –1910), the American philosopher and psychologist considered to be the father of American psychology delivered a lecture on the solar system, he was accosted by an elderly woman, who claimed that she had a better theory – that the crust of the earth rested on the back of a giant turtle. When he asked what the giant turtle was standing on, she replied on the back of an even larger turtle. "And what is that turtle standing on?", he inquired. "Why it's turtles all the way down." Originating with the Hindu myth that the world is carried on the backs of four elephants standing the back of a giant tortoise, the anecdote is commonly used as a philosophical metaphor to illustrate the concept of infinite regression.

Moses: But how could you ever prove it? Suppose that in our universe with three fully accessible space dimensions, there's a black hole with two fully accessible space dimensions, and inside it there's a black hole with only one fully accessible space dimension. If we can't extract any information from the inside of the black hole with two fully accessible space dimensions, then how could we ever detect whether there's a black hole with only one fully accessible space dimension inside it?

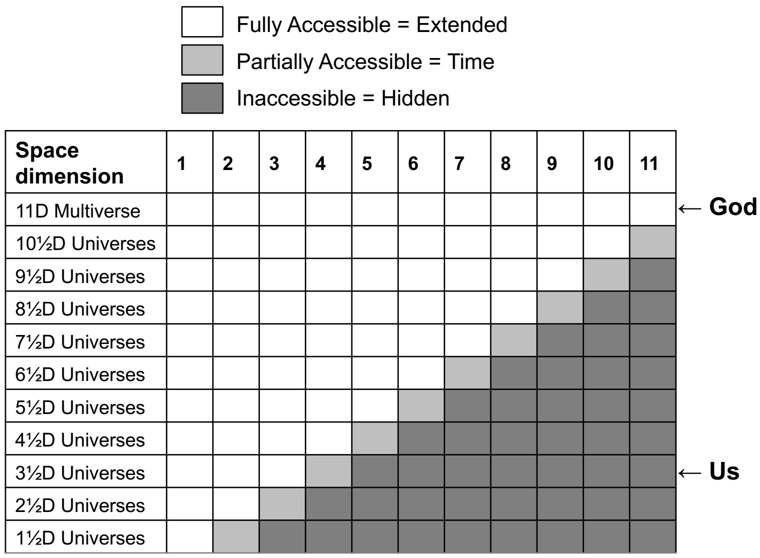

Figure 8-1. The hypothetical timeless multiverse with 11 space dimensions. When a black hole forms in the eleven dimensional (11D) multiverse, a fully accessible extended space dimension (white squares) in which forward and backward movement are both possible becomes partially accessible (light gray squares) such that only forward movement towards the singularity is possible, which we perceive as time, creating a 10½D universe. When a black hole forms in a 10½D universe, the partially accessible dimension becomes inaccessible as a hidden dimension (dark gray squares) and the next fully accessible space dimension becomes partially accessible as time, creating a 9½D universe, and so forth. Humans (Us) exist in a 3½D (equivalent to a conventional 4D space-time universe in which time is considered a full dimension on its own). God exists in the timeless 11D multiverse. The universe to which M theory applies (ten space dimensions and time) corresponds to the 10½D universe.

Socrates: I didn't claim that it would be easy. No one really knows what laws of physics apply inside a black hole, because no information can escape from it. But it's the same situation with M theory and the multiverse – strange ideas about reality that leading theoretical physicists take very seriously, even though they aren't yet supported by any conclusive experimental evidence. But what if those physicists someday figure out how to do an experiment to prove that the multiverse exists? Then maybe they can figure out how to look inside a two-dimensional black hole to find a one-dimensional black hole. Or detect a universe with four fully accessible space dimensions and time, in which our universe is a black hole with three fully accessible space dimensions and time.

Moses: In that case, if we could someday detect these higher dimensional universes, what do you think that the full eleven dimensional multiverse would look like, if you weren't trapped in any black holes?

Socrates: That, my good friend, is the whole point of this 'black holes-within-black holes' exercise in imagination! The conventional multiverse on which the mathematical formulation of M theory is based contains ten space dimensions and time. In our terminology, that would correspond to a 10½ dimensional universe, with ten fully accessible space dimensions and one partly accessible space dimension collapsed by a black hole into time. If there are really eleven space dimensions in all, and none of them have yet collapsed into black holes, *then the actual eleven-dimensional multiverse would have no time!* You could move unrestricted, backward or forward, in all eleven space dimensions. Past, present and future all realized at once – the multiverse, in its full, blazing, eternal timeless glory!

Moses: Now I get it. If you need God to be outside of time, then the natural place for God to exist would be in the eleven-dimensional multiverse itself, with complete instantaneous access to all eleven space dimensions!

Socrates: There you go. We may just have found God's hiding place!

Moses: It truly boggles the mind. What if M theory is right and scientists someday do figure out a way to detect and study these extra dimensions in the multiverse? Then in principle at least, it might be possible to devise an experiment to test whether there is a God lurking in the multiverse! Think of it – a bone fide scientific experiment to find God! Logical reasoning and belief in God reunited, at long last!

Socrates: And science united with religion at last!

Moses: I don't know if I'd go that far. Do you really believe that there's a chance that science and religion can ever be fully reconciled?

Socrates: That's what I love about modern physics – the scientific ideas about the nature of reality have become so strange and nonintuitive that most religious beliefs seem tame by comparison.

Moses: I have to admit, it's a noble goal to imagine both science and religion working together, side-by-side for a change, to develop a consensus on the best principles for humans to live by. Bringing religion to the rational and science to the spiritual!

Socrates: Perhaps we should give our new belief system a name.

Moses: What do you suggest?

Socrates: How about ReliEnce - the first four letters of religion and the last four of science?

Moses: Great idea, I like it! Our motto can be "You can rely on ReliEnce," with God as the Creator of the Axioms of the Universe, and science explaining how everything knowable in the universe flows from those axioms!

Socrates: Praising God and science together as the unknowable and knowable parts of universe, life and everything else, respectively! That should appeal to just about everyone. And with God as the unknowable part, God can be imagined however you like - a white-haired patriarch on a throne, Yahweh, Jehovah, Allah, the duality of Ahura Mazda and Angra Mainyu, *Amatongo*, ancestral spirits, a higher power, the Laws of Nature, whatever you feel the most comfortable with!

Moses (interrupting): Okay, I get the idea. If the unknowable part of the universe, life and everything else is truly unknowable, then who can object to how other people prefer to envision God? God can mean different things to different people.

Socrates: Exactly, and it also fits with biblical references to God as That-Which-Has-No-Name. After all, how can speak knowledgeably about something that you know nothing about?

Moses: An excellent point, although there are many humans, especially politicians, who attempt it all the time!

Socrates: I have to say, Moses, I am quite thrilled by your new enthusiasm for the ecclesiastical! I think that we should commemorate the occasion. Please be so kind as to kneel.

Moses: Why?

Socrates: You'll see.

Moses (kneeling): Okay, if you say so.

Socrates: Moses, with the powers invested in me, I hereby anoint you as the First Prophet of ReliEnce. You may now rise.

Moses: Wow, I wasn't expecting that.

Socrates: Well, what to you say?

Moses: I don't really know if I'm cut out to be a prophet.

Socrates: Don't be silly – with your name, you're a natural! I hope you're not getting cold feet over our great plan to heal the rift between religion and science.

Moses: Hey, even if I wanted to be a prophet, I would have no idea how to go about it.

Socrates: It's simple. Just believe in yourself and your mission, and then go forth and proselytize! Besides, with me as a loyal disciple by your side every step of the way, how can you possibly fail?

Moses: I guess that makes all the difference, having a loyal sea lion by my side. Then people will really think I'm crazy!

Socrates: Come now! Miracles like burning bushes and parting seas have a distinguished place in the history of prophethood. Maybe your miracle can be a talking sea lion! I can pretend to be mute and then burst into speech when you wave your staff.

Moses: Very amusing.

Socrates: Just a suggestion. If it's not your style, we can take a less flamboyant approach.

Moses: And what would that be?

Socrates: Take the relevant holy scriptures - the Upanishads, the Vedas, the Old Testament, the New Testament, the Qu'ran and all the others that you can think of – and do your best to reconcile them with modern science.

Of course, you have to be diplomatic. If you expect a Bible-thumping fundamentalist to accept bizarre concepts like hidden dimensions and the multiverse, then you need to be respectful of what the bible claims, and not just dismiss it as ridiculous superstition. The more you show respect for the holy scriptures, the less you will upset your religious colleagues. My advice is to focus on things that you can agree on, like the Ten Commandments and the Golden Rule, rather than picking contentious topics to argue about.

Moses: Sounds great in principle. But in practice, so many religious beliefs conflict with science. I'm not sure that there will be all that much to agree on.

Socrates: That's what I love about modern physics – it has a lot of built-in flexibility, just like scriptures. Why don't you give me an example, and let's see if we can figure out a compromise?

Moses: Okay. How about the earth being the center of the Solar System?

Socrates: I hate to break it to you, but the Church gave up on that idea a long time ago. The Pope even issued an official papal apology to Galileo, although it was a few centuries late [58]. And as much as Galileo deserved the posthumous apology, the irony is that Church wasn't really wrong about the sun orbiting the earth.

Moses: What do you mean? Even the Church now accepts the earth rotating around the sun, not the other way around. How can you say that the Church was right and Galileo was wrong?

Socrates: I didn't say that Galileo was wrong about the earth orbiting the sun. But, according to modern physics, he was wrong to conclude that the sun does not orbit the earth. And conversely, the Church was right that the sun orbits the earth, but was wrong to insist that the earth does not orbit the sun. So as I see it, it is pretty much a draw.

Moses: You're not making sense. You can't choose both.

Socrates: Why not? Maybe it's like the square root of four, with more than one correct answer.

Moses: I'm listening.

[58] In 1992, Pope John Paul II issue a formal apology to Galileo for his mistreatment by the Roman Catholic Church.

Socrates: Albert, 1905, the *annus mirabilis* [59]. That was the year he published his paper on special relativity, which, as you recall, states that there is no preferred frame of reference in the universe – or more precisely, that the human mind, using the laws of physics, cannot distinguish an absolute frame of reference that is at rest and not moving relative to all other frames of reference. All humans can detect is the relative motion between two frames of reference. Like if you are standing in a train station and a train speeds by, you would think that you are stationary and the train is moving. But in reality, the station is not really at rest – it's moving through space as the earth turns. So all that you can really say is that the station is not moving relative to you, but the train is.

Moses: I still don't see why that means the sun is rotating around the earth, instead of the other way around.

Socrates: Because you can solve Isaac's Laws of Motion to calculate the motion of the earth relative to sun, or alternatively, the motion of the sun relative to the earth just by translating coordinates to the appropriate frame of reference. Either way, the orbits are ellipses (Figure 8-2).

Moses: Really? Then why do we always think of the sun as being at the center of the solar system?

Socrates: Because if you use the Copernican frame of reference, with the sun at the center, then all of the other planets, like Mars for instance, also make simple elliptical orbits around the sun (Figure 8-2, left). On the other hand, if you use the Ptolemaic frame of reference with earth at the center, then the other planets, like Mars for instance, make more complicated orbits around the earth, with extra loops called epicycles (Figure 8-2, right). Either way, the precision of the calculations are equivalent. So that's how Galileo and the Church could both be right, despite their seemingly diametrically opposed positions. Assuming that you accept the validity of Newton's laws and special relativity, that is.

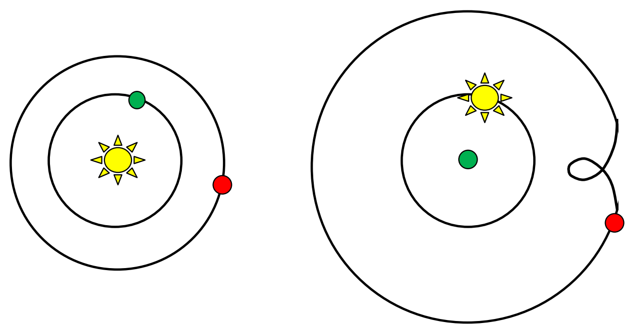

Figure 8-2. ***Left:*** The **Copernican solar system** with the Earth (green) and Mars (red) rotating around Sun (yellow). ***Right:*** The **Ptolemaic solar system** with the Sun and Mars rotating around the Earth. The Mars orbit is now double-looped due to an epicycle, as are the orbits of other planets.

[59] In 1905, subsequently known his annus mirabilis (the miracle year), **Albert Einstein** (1879 –1955) published four ground-breaking papers that contributed substantially to the foundations of modern physics. The first paper elucidated the theory of the photoelectric effect; the second paper explained Brownian motion; the third paper introduced special relativity; and the fourth, mass-energy equivalence.

Moses: Okay, I stand corrected. But there are so many other absurd claims. How about the age of the universe? According to the Bible, the universe is only 6,000 years old, while scientific evidence dates the Big Bang that created our universe to some fourteen billion years ago. Let's see you talk your way out of that one.

Socrates: Easy. If M theory is correct and there is a multiverse, then alternate universes are being created every moment in time, and always have been. Thus, if you accept our most sophisticated current scientific theories, a universe from which our universe has evolved did spring up six thousand years ago, just like the Bible says. It also sprang up 14 billion years ago. So technically, both modern science and the Bible are correct.

But today, most religious people don't believe that the earth is at the center of the solar system, or that the earth is only six thousand years old. Why don't you pick a controversy that's relevant to today's world.

Moses: Okay, then how about the controversy between evolution and intelligent design? What do you say to creationists who insist on giving equal status to both in a high school biology class?

Socrates: Intelligent design is a religious theory, not a scientific theory, and therefore doesn't belong in a biology class any more than Darwin's Theory of Evolution belongs in a religion class. But it's not unreasonable to teach them both together in a philosophy class, so that young minds can debate the relative merits and weaknesses and come to their own conclusions. For scientists to make their arguments about the origins of our universe, life and everything else logically rigorous, they can't ignore the fact that scientific reasoning can't explain how the Axioms of the Universe came into existence. The Laws of Nature themselves cannot explain why the Laws of Nature exist. So if an explanation is to be had, it must come from outside of the Laws of Nature, whether you choose to call it supernatural or divine. A perfect topic for a philosophy class!

Moses: I'm glad that you brought up the Laws of Nature. It reminds me another difference between religion and science that seems pretty irreconcilable.

Socrates: What's that?

Moses: Miracles. Like the Moses receiving the tablets with the Ten Commandments from God, or Jesus magically turning water into wine. Miracles are such an essential component of religious beliefs, but they directly violate the Laws of Nature, which is anathema to scientific thinking. How do you expect to ever resolve that?

Socrates: To be honest, the whole controversy over miracles seems a bit silly to me. So-called miracles are one-time events – by definition, they are not reproducible in a controlled experiment and therefore are inherently not verifiable through science, even when the event is well-documented.

Moses: Still, it matters a lot to both sides. Scientists tend either to dismiss them as hallucinations or deceptions, or fall back on the argument that even if they appear to violate Laws of Nature as we understand them today, they will be explained eventually as science advances.

Socrates: True, but until you have a definite scientific or psychological explanation, you can't exclude the possibility that some rare one-time event was a genuine miracle. Especially if you accept the position that modern physics is only capable of describing "model-dependent reality" [60], rather than reality itself. If we can never distinguish true reality from a model of reality, who can ever really know whether a rare irreproducible event falls within or outside of the true Laws of Nature? In any case, for you, miracles are not an issue of contention, since you've accepted an impersonal God who just set the universe in motion and then stepped back and never intervenes. In that case, God doesn't perform miracles.

Moses: It's not me that I'm concerned about. It's the religious people who believe in a personal God that does intervene in the daily workings of the universe.

Socrates: Even so, I don't think that the miracle issues needs to be a deal-breaker. All you have to do is think creatively and flexibly. Perhaps the M theory and the multiverse hold the answer.

Moses: An explanation for religious miracles? This I can't wait to hear.

Socrates: How about this? In our version of the multiverse with eleven fully accessible space dimensions and no time (Figure 8-1), God exists outside of time. You and I, on the other hand, are trapped in black holes within black holes, resulting in both our perception of time and seven hidden compactified dimensions to which we have no access. Then we also raised the possibility that there may be other universes that have different numbers of fully accessible space dimensions, anywhere from one to eleven, right?

Moses: So far so good.

Socrates: That's where it gets intriguing, especially if you agree with your scientific colleagues who argue that it is statistically almost certain that life exists elsewhere in the universe. [61]

Moses: That is a pretty popular idea these days.

Socrates: Then if there are countless other universes with different numbers of fully accessible space dimensions, some of them may have conditions favorable to life, and also evolved intelligent lifeforms.

Moses: I suppose. But they would have to be totally different from the kind of life forms that we're familiar with, if they exist in universes with a different number of accessible dimensions than ours.

Socrates: My point exactly – they'd have access to different space dimensions of the multiverse than we do. Now suppose that they were to share some of the same

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[60] **Stephen Hawking** and **Leonard Moldinov.** *The Grand Design.* Bantam Books, 2010.

[61] Since there are trillions of stars like ours, and about one in five has a planet orbiting in the "Goldilocks" zone (not too hot and not too cold, to permit liquid water, a basic requirement for biological life as we know it), it is speculated that given 14 billion years, the odds are that life has evolved on more than just earth.

dimensions with us. If they are intelligent lifeforms, then perhaps they could find a way to communicate with our universe.

Moses: And possibly interact with us?

Socrates: Not only that. What if they had full access to the space dimension that we have only partial access to – the one that we perceive as time? They would be able to move both forward and backwards in that dimension, whereas we can only move forward.

Moses: In other words, they could time travel in our universe?

Socrates: Exactly. Those higher dimensional beings could just suddenly appear and disappear in front of our eyes. That could explain visions of god, or angels or demons! And maybe miracles, too. If higher dimensional beings could time travel to come and go as they please in our universe, they could suddenly appear out of the blue in front of Moses with a set of stone tablets inscribed with the Ten Commandments, or switch the water for wine at Jesus's party without anyone witnessing it.

Moses: Pretty crazy idea. How do you come up with these explanations?

Socrates: Like I said, M theory and the multiverse open up whole new vistas of possibilities that would seem utterly absurd from the perspective of classical physics.

Moses: So science could potentially have an actual shot at explaining miracles and visions within the Laws of Nature, instead of just dismissing them out of hand as hallucinations. None of this seems to have occurred to the multiverse crowd yet – most of them are confirmed atheists.

Socrates: Yes, I've noticed that. A bit ironic, don't you think?

Moses: Why?

Socrates: Because until the past hundred years or so, most scientists were not atheists – they viewed scientific discoveries about the universe as God revealing to humans the magnificence of his/her creation. Like when Sir Isaac referred to infinite space as the *"sensorium"* of God, as a way to explain the Lord's omnipresence and omniscience[62]. Gottfried, who was also a believer, laughed at him for it, *"As if God, from whom everything comes, should have need of a sensorium."* But the point is, neither of them doubted God's existence, they were just arguing about God's attributes.

Moses: But science was still in its infancy then. It didn't yet have its amazing track record at explaining natural phenomena. Once you have an explanation for how the solar system operates and how life evolves through natural selection, it's harder and harder to subscribe to superstitious beliefs. That's why beyond the nineteenth century, more and more scientists consider themselves to be atheists or agnostics – over 90% of members of the National Academy of Sciences in the US today.

[62] **James Gleick**, *Isaac Newton* (Vintage Books, 2003). p. 167

Socrates: Whereas 90% of non-scientists in the US believe in God. That statistic alone would seem to me to be a very good reason why scientists should strive to win over the non-scientists, if they really ever hope to make the world a better place through science. And by win over, I don't mean by convincing them to give up their belief in God, like the "New Atheists" who insist that modern science has proven the God hypothesis to be false, and dismissing scientists who are not atheists or agnostics as apologists [63]. By winning over, I mean finding a path of compromise.

Moses: I have to admit that the multiverse brings with it a lot of interesting new possibilities in that regard. Especially now that I have direct evidence that alternate universes actually exist.

Socrates: What do you mean?

Moses: Well, here I am discussing the existence of God with a sea lion. Ergo, I must be in an alternate universe right now!

Socrates: Ha-ha, very funny!

Moses: Maybe you are one of those higher dimensional beings who can travel in time!

Socrates: I'm flattered that you might think so. But alas, I am just a humble spirit like yourself, trying to make some sense out of the world. Besides, right now the multiverse is still a theory that has yet to be experimentally validated.

Moses: But if scientists are willing to seriously consider such bizarre ideas about nature of reality, even in the absence of direct experimental evidence, then perhaps they should be a bit more open-minded about the possibility that religious beliefs, even those that appear to violate the Laws of Nature, may not necessarily be incompatible with science. It's certainly true that many observations that once seemed to violate the Laws of Nature according to classical physics have now been successfully explained by modern physics.

Socrates: Exactly my point. If scientists didn't reflexively dismiss religious beliefs, then perhaps ReliEnce would stand a chance.

Moses: And the same goes for religious believers being more open-minded. I suppose that one good thing about the Bible is that its passages contains so many contradictory precepts that you can generally pick and choose among them to construct a theological argument that agrees with a scientific argument.

Socrates: Exactly. It may not work for every argument, but the Bible and other holy scriptures contain a lot of inherent flexibility, even when interpreted literally. Science does too, when you think about it.

Moses: What do you mean?

Socrates: Say you have a problem whose solution has two answers, like the square root being either +2 or -2. How does the scientist know which answer is correct?

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[63] **Richard Dawkins.** *The God Delusion*. First Mariner Books, 2008.

Moses: Sometimes, it only makes sense if the four came from squaring +2. Like if the area of a square is four cm^2, then it only makes sense if the two sides are each +2 cm in length, since there is no such thing as negative length.

Socrates: Very good. So the answer depends on additional information about the nature of the problem. That is, it depends on context. Just like the Talmudic scholar who said that if even a simple question like the square root of four has more than one correct answer, how could you expect life's complex questions about ethics and morality to have only one correct answer? In that regard, religion has a lot of valuable experience to offer. There's a reason why holy scriptures such as the Bible contain conflicting passages like *"Whoever sheds man's blood, his blood will be shed by man, for God made man in His image*" on the one side and *"Thou shalt not murder"* on the other. Or *"An eye for an eye"* on one side and *"Turn the other cheek"* on the other. Even fundamentalists, who interpret scriptures literally, have tremendous flexibility in choosing the appropriate premises to arrive at a conclusion that takes context into consideration.

Moses: Somehow, that seems manipulative, if you can arbitrarily choose whatever premises best suit the argument that you are trying to prove.

Socrates: That's even more reason why it makes sense to use scientific and religious reasoning together to decide on the best way to solve a problem. Science and religion approach problems from completely different perspectives, using completely different sets of premises. So if they arrive at the same conclusions from different directions, the answer is more likely to be helpful towards working out a solution. It may not work for every argument, but when it comes to complicated ethical and moral questions, does it really matter, in the end, whether the answers are based on scientific premises or God-given premises, as long as the moral principles are fair and just? If both sides keep an open mind, it should possible for people of science and people of faith to work together and focus your combined energies on the really important questions facing humankind!

Moses: That would certainly be a wonderful goal to work towards!

Socrates: Indeed, it would. I hope that you will take it to heart.

Moses: You know, we've covered a lot of ground, considering where we started from.

Socrates: You mean from Protagoras's claim that "Man is the measure of all things?"

Moses: Yes.

Socrates: We have indeed. And what do you think about Protagoras's claim now?

Moses: I think Protagoras was wrong.

Socrates: How so?

Moses: If part of the universe is unknowable, then we cannot measure it. And if there is something that we cannot measure, then we can't be the measure of all things.

Socrates: One small flaw in your argument.

Moses: How so?

Socrates: You said "If part of the universe is unknowable, then we cannot measure it". What you should have said is: "If part of the universe is unknowable through scientific reasoning, then we cannot measure it through science". Maybe man can measure things through other means, like faith. Then man could still be the measure of all things.

Moses: Nothing escapes you, does it?

Socrates: I hope not - I've been at this a long time.

PART II: Life

ODE TO LIFE

Like the great serpent Ouroboros
eating its own tail,
Life strives to survive at all costs,
Digesting what's Good Enough
And discarding the detritus,
Consuming herself to renew herself,
Emerging, Adapting, Evolving,
Replacing what's Old
To create what's New,
Life is
The ultimate Machina ex Deus.

A drawing of the Ouroboros, an ancient alchemical symbol which symbolizes eternity & the circle of life and death, from the Synosius by the Greek bishop Synesius (373-414 AD).

CHAPTER 9: Self-Organization

Moses: What about life? You corrected me by saying "If part of the universe is unknowable through scientific reasoning, then we cannot measure it." Where do you think life falls – is it knowable or unknowable through science?

Socrates: A lot of life is knowable through science, but not all of it. How could it be? Logical reasoning tells us: If *science can't tell us how the Axioms of the Universe came into being* and *life is part of the universe that arose from those Axioms*, then *science will never be able to reveal fully how life came into being*.

Moses: Okay, if you're going to be so picky, then let me rephrase the question. Assuming scientists someday come up with a Theory of Everything whose most fundamental premises are solid candidates for the Axioms of the Universe, then do you think that life will be fully explainable by that Theory of Everything?

Socrates: That's certainly the dream of science. It really wouldn't be a Theory of Everything if it didn't explain life, would it? Besides, a Theory of Everything isn't really expected to explain "EVERYTHING", since it can't explain where the Axioms of the theory came from in the first place. To be accurate, it really should be called a Theory of Everything That Can Be Explained by the Theory's Axioms. Or, for short, a Theory of Almost Everything.

Moses: Wow! You are being a stickler. Let me try one more time. If scientists do someday come up with a credible Theory of Almost Everything, do you think it will it be able to explain life, or will something more be required?

Socrates: Like a soul or some mysterious life force, you mean?

Moses: Exactly. What do you think?

Socrates: Let's take stock of where you are. Right now, your purported candidate Theories of Almost Everything, such as M Theory, focus mainly on the fundamental stuff that the universe is made of. Their axiomatic assumptions fall into three categories: a set of ingredients, like various particle-waves and fields; a set of laws governing the behavior of those ingredients, such as M theory; and a set of initial conditions describing the state of those ingredients at some initial moment. Those assumed axioms give rise to all of the far out stuff that we've been talking about.

Moses: Sure, like the Big Bang, quantum gravity, hidden dimensions, black holes, quantum entanglement with its spooky action-at-a-distance, and so forth.

Socrates: Exactly. But those sets of axioms, by themselves, are still not quite enough to explain why time moves only in the forward direction for everything beyond the subatomic particle-wave level, which obviously includes all living organisms. For that, you also need to add the Second Law of Thermodynamics as an additional axiom.

Moses: And is that enough to account for life, in your opinion?

Socrates: It may well be enough to explain from first principles how various molecular pathways function within a living organism. But whether it's enough to explain how those molecular pathways self-assemble themselves through Laws of Nature to create the spark of life is hard to say.

Moses: What about all of the progress we've already made, like how the genetic code works through DNA and RNA, how organs like the kidneys and heart perform their functions, how nerves transmit information electrically in the brain, how evolution works through natural selection, and all sorts of things?

Socrates: Applying the laws of physics and chemistry to biology has led to many fundamental insights into the molecular basis of living systems, from microrganisms to mammals. Those are wonderful discoveries. But merely breaking down a living organism into its components isn't enough to explain life. You can't just dump all the essential ingredients into a flask and expect a living organism to crawl out.

Moses: True, but we've only been at it with modern science for a few hundred years. Don't you think it's just a matter of time before we figure it out?

Socrates: Maybe. The biggest challenge you face now is how all of those molecules spontaneously self-assemble and self-organize themselves into the molecular complexes, pathways, organelles, cells, tissues, and organs that make up a living organism. First, you need to figure out the critical step that confers to an egg the ability to generate a living organism once fertilized. After that you need to explain how that fertilized egg spontaneously differentiates into different organs and then how those organs are functionally integrated in the body of a living organism. For humans, that includes how high level functions like consciousness, self-awareness and reasoning develop. Life has to do that all on its own, spontaneously, without any master engineer to direct the process.

Moses: That's a pretty tall order. So how does it happen?

Socrates: It has to be more than just the constituent molecules like DNA, RNA, proteins, lipids, carbohydrates, etc. As the fable says, all the king's horses and all the king's men couldn't put Humpty Dumpty together again. Scramble an egg and it will become a chicken.

Moses: But you could also say the same for a machine. If I took a radio apart, and put all of parts into a paper bag, I could shake that bag as long as I wanted and the radio would never reassemble itself to be able to play music.

Socrates: True. However, you could get a master electrician who knows how the parts fit together to reassemble the radio. But a cell has to do that all by itself – there's no master technician standing by to direct its assembly or repair it if it breaks. So how does an egg know what to do?

Moses: It's programmed to self-assemble, I guess. Like an automated assembly line.

Socrates: But who wrote the program?

Moses: We're not going back to the God discussion again, are we?

Socrates: No, that would be the easy way out.

Moses: What about all of those dynamical behaviors that we discussed before, like the straight-in and spiral attractors, straight-out and spiral repellers, saddles, centers, oscillators, bistability, excitable elements and strange attractors (Figure 5-2)? You claimed that they are the fundamental building blocks for all of the behaviors observed in nature, just like resistors, capacitors, transistors and voltage and current sources are the fundamental building blocks for everything in electronics from toasters to televisions. Since life is a type of behavior observed in nature, shouldn't it also be explainable as a combination of those same building blocks, just like other natural phenomenon? I realize that we still have a long way to go, but don't you think that's the most likely logical explanation?

Socrates: Personally, I would hope so, since everything in life, from the moment of conception, depends on clocks, switches, excitable elements and spontaneous pattern formation mechanisms to turn cell division on and off, control organ development, generate the heartbeat, breathing, sleep-wake cycles and circadian rhythms, and every other vital function that I can think of!

Moses: Then how can science move forward to figure it out?

Socrates: Perhaps before looking forward, you should look backward.

Moses: What's that supposed to mean?

Socrates: Just saying, perhaps some ancient holy wisdom will help. That was a key goal that we set for ReliEnce, remember, to synthesize religious and scientific thinking to help us better understand the world.

Moses: What ancient holy wisdom do you have in mind?

Socrates: I was thinking of Yin and Yang.

Moses: The ancient Chinese philosophy? [64]

Socrates: Exactly. Dual opposing elements that harmoniously unify to achieve movement and change. Or, in modern terms, complementary opposing forces interacting to create a whole that's greater than the sum of the parts. Perfect for ReliEnce, don't you think - wisdom that's ancient and modern at the same time!

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[64] In Ancient Chinese philosophy, **Yin and Yang** (lit. "dark-bright", "negative-positive") is a concept of dualism, describing how seemingly opposite or contrary forces may actually be complementary, interconnected, and interdependent in the natural world, and how they may give rise to each other as they interrelate to one another. In Chinese cosmology, the universe creates itself out of a primary chaos of material energy, organized into the cycles of Yin and Yang and formed into objects and lives. Yin is the receptive and Yang the active principle, seen in all forms of change and difference such as the annual cycle (winter and summer), the landscape (north-facing shade and south-facing brightness), sexual coupling (female and male), the formation of both women and men as characters and sociopolitical history (disorder and order).

Moses: Aren't the traditional opposites in Yin and Yang things like light/dark, order/disorder, active/receptive, male/female, north/south, and so forth? How is that going to help us understand how life works?

Socrates: Remember when we said that everything in nature is a balance between attractive and repelling forces? If nature contained only attractive forces, then all objects, whether subatomic particles or galaxies, would be drawn together towards a single point, creating a single infinitely dense object like a black hole. But if nature contained only repelling forces, all objects would move apart from each other until they became infinitely dilute. In either case, stable objects bounded in space and time would not be able to form, whether you're talking atoms, galaxies or any of the inanimate and animate things in between. To me, that's the most basic organizing principle for everything in nature. It's also the modern version of Yin and Yang - that every bounded object in the universe is formed and stabilized by the tension between opposing but complementary forces. We just need to update the list of opposing forces a bit.

Moses: Like how?

Socrates: For example, in physics, the pairs are attractive/repelling and order/disorder. In chemistry and biology, it's activators/inhibitors. For evolution, ecology, economics and the social sciences, they're cohesive/disruptive, cooperative/uncooperative, selfish/selfless and so forth.

Moses: So you really believe that this Yin and Yang idea is the fundamental organizing principle for everything in nature, including life?

Socrates: Of course.

Moses: In other words, sort of like another Axiom of the Universe – the Yin and Yang Axiom?

Socrates: More like a set of Axioms, really. First, there is the set of ingredients - all of those fundamental dynamical building blocks like attractors and repellers that we listed before. Next, there are the rules by which they interact. And finally, the state of the ingredients at some initial moment.

Moses: But how do you establish whether those are really Axioms in their own right? Shouldn't they ultimately be derivable from more fundamental Axioms of the Universe, like those emerging from a Theory of Almost Everything like M Theory.

Socrates: That's certainly the ultimate dream of science, to end up with the smallest set of Axioms possible. "As simple as possible, but not simpler," as Albert would say.

Moses: Then maybe we should provisionally call it the Yin and Yang Principle instead of the Yin and Yang Axiom.

Socrates: Fine with me.

Moses: So explain to me how does this Yin and Yang Principle applies to life.

Socrates: The key element is feedback. That's how the complementary opposites interact with each other. Positive feedback pushes the system away from an equilibrium state, and then negative feedback pulls it back towards the equilibrium state. That's the formula for how spontaneous patterns emerge in time and space. Take the logistic equation, for instance. Depending on the steepness of the positive and negative feedback, the system could be stable, oscillate or even behave chaotically (Figure 3-3). None of those behaviors were being imposed on the system by external factors - they were intrinsic to the system itself.

Moses: Not to be skeptical, but the logistic equation is just a mathematical equation for a parabola. How does that apply to the real world?

Socrates: If you want a real world example, how about the furnace that keeps you warm on cold winter nights? Have you ever noticed how the furnace turns off and on intermittently when it's heating your house, despite the thermostat being set at a constant temperature? Why do you think that is?

Moses: It's hardly a mystery. The furnace turns off when the temperature in the house rises above the thermostat's setpoint, and then turns back on again when the temperature falls below the setpoint.

Socrates: A very artful restating of what I just said, congratulations! But that's a description, not a mechanism. How feedback is involved?

Moses: I suppose that when the temperature sensed by the thermostat exceeds the setpoint and the furnace turns off, you could call that steep negative feedback.

Socrates: Very good, Moses! Negative feedback does indeed turn the furnace off. But since there's still a lot of hot air in the ducts and the furnace takes time to cool down, the temperature recorded by the thermostat continues to rise and overshoots its mark. Only after the hot air is finally cleared from the ducts does the temperature then start to decrease. When it eventually falls below the setpoint and the furnace turns back on full force, what would you call that?

Moses: Steep positive feedback.

Socrates: Right again. Positive feedback turns the furnace back on. But once again, because of the time delay for the furnace to heat the air and push it through the ventilation ducts, the temperature in the room continues to fall. And so it goes, with the furnace turning off and on and temperature oscillating instead of remaining dead-on at the setpoint. Feedback plus a time delay, a classic formula for generating oscillations!

Moses: Makes sense when you explain it like that. But I don't think my furnace turning off and on would make a very reliable clock for a living organism, especially in the summer when it's sweltering outside and the furnace never turns on. If that were my heartbeat, I'd be in trouble.

Socrates: Then how about a grandfather clock, the kind driven by a pendulum. When you raise the arm of the pendulum to one side and release it, positive feedback by gravity causes it to gain speed until it reaches the lowest point at the center. After that, negative feedback causes it to slow progressively until it reaches its high point on the other side. The interaction between the alternating positive and negative feedback causes the pendulum to swing back and forth, tick-tock as a clock. Same principle.

Moses: That's a better example. What about patterns in space? Can feedback explain them as well?

Socrates: Funny you should ask, because there's a great example staring you in the face, right over there on the beach!

Moses: Where?

Socrates: Do you see the ridges in the sand over there? Notice how regularly spaced they are, about a foot or so apart (Figure 9-1A). How do you suppose those ridges formed?

Moses: It could be related to a similar pattern of ridges in the rocks below the sand.

Socrates: It could be, but I'd bet that's not what you'd find if you washed away the sand. There are stones and boulders underneath the sand there, not regular ridges.

Moses: I suppose you're right. That probably isn't the correct explanation.

Socrates: What about the way the ridges are aligned?

Moses: They seem to be parallel to the shore, for the most part.

Socrates: And which way does the wind usually blow here?

Moses: It's usually offshore. Why?

Socrates: Because if the ridges are parallel to the shore, then they are perpendicular to the wind.

Moses: So what?

Socrates: Think of what happens if the wind picks up a few grains sand from some random location near the

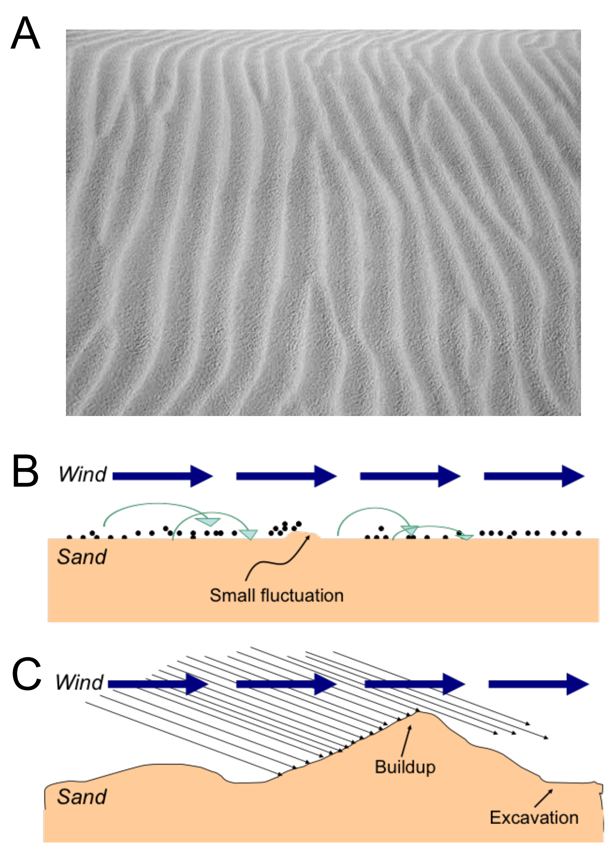

Figure 9-1. A. Sand ridges formed by the wind on a beach. **B.** Wind picks up grains of sand and deposits them downwind, forming a small ridge. **C.** Grains pile up on upsloping nearside of the small ridge, but not on the downsloping farside, causing the ridge to grow in size and a new ridge to form beyond where the grains can finally land, and so forth.

shoreline.

Moses: It would carry them downwind.

Socrates: Exactly, leaving a small depression where they were picked up and a small ridge where they landed (Figure 9-1B).

Moses: I suppose.

Socrates: And if the wind now picked up a few more grains of sand near the same location, where would they be likely to land?

Moses: Now I see where you're going. They'd be more likely to land on the upsloping nearside of that small ridge, rather than on the downsloping farside (Figure 9-1C).

Socrates: Exactly! The grains of sand are more likely to land on the ridge's upslope because of its steeper angle to the wind. It's a setup for positive feedback, since the higher the ridge grows, the more likely the grains of sand are to land on it.

Moses: And what about the negative feedback component?

Socrates: The negative feedback occurs whenever a grain of sand lifted by the wind happens to make it over the top of the first ridge. Since the ridge's downslope is at a shallow angle to the wind, the grain is less likely to land on it. But once the sand becomes flat again, the grain will land, building a new ridge behind the first by the positive feedback.

Moses: I see. So a second ridge builds up after the first ridge.

Socrates: And a third ridge past the second ridge, and so forth, due to the alternating zones of positive and negative feedback. The distance between the ridges of sand ridges is determined by the how far the sand grains are carried by the wind, so that stronger wind or lighter grains of sand make the ridges spaced more widely apart, and vice versa.

Moses: But on a real beach, wind velocity and direction is constantly varying, and sand isn't completely flat. How can you exclude the possibility that the wind isn't just amplifying those small initial heterogeneities?

Socrates: Because in a computer model, you can create a mathematically pure wind and mathematically flat sand, and show that the same spacing pattern and height of ridges always emerges, even though the starting position varies depending on where the first grains of sand are randomly lifted by the wind. On a real beach, the variations in wind and pre-existing unevenness in the sand affect where the ridges start and can make the ridges branch and curve, but the basic features of the pattern are similar.

Moses: It is pretty amazing that a pattern like that can generate itself completely spontaneously by a self-organizing process, without requiring a master ridge maker to create it.

Socrates: All you need is wind and sand!

Moses: One question, though.

Socrates: What's that?

Moses: In your computer model of the wind and sand, the underlying mathematical equations are deterministic, right? If so, then formation of the ridges is also completely deterministic.

Socrates: Correct, but so what?

Moses: Then where does randomness fit in, given that nature is fundamentally probabilistic, starting with quantum uncertainty?

Socrates: Actually, randomness plays a critical role. Remember when I asked you what happens when the wind picks up few grains sand?

Moses: Sure – those grains started the first small ridge.

Socrates: Exactly. That random event, the random location where the first grains of sand were picked up, is what starts the whole pattern-forming process. It's what breaks the symmetry of the previously flat sand-wind interface to start the first ridge. Only then can the positive and negative feedback take hold to amplify the initial small ridge and generate the repeating pattern over a whole section of the beach.

Moses: So nature is actually harnessing randomness to generate order!

Socrates: Indeed. Nature is very clever that way. And so is life, as part of nature! It's a very similar process that generates patterns in biology, like the stripes and spots on tigers and leopards, the elaborate skin patterns on those fish swimming below us, the formation of organs, appendages, heads and tails. But instead of wind and sand, the players in living systems are biochemical reactions. So, do you still think that Yin and Yang is merely a religious superstition?

Moses: I guess not. Go ReliEnce! Who was the scientific genius who figured all of this out?

Socrates: I'll give you a hint. He was the conceptual father of the modern computer. Also the codebreaker who saved Britain, and possibly the world, from Nazi conquest.

Moses: Alan?

Socrates: Correct. In 1952, just two years before his suicide, Alan published a truly ground-breaking theoretical paper demonstrating how feedback in chemical reactions produces self-organizing spatial patterns. They're called Turing patterns in his honor [65].

Moses: How does it work?

Socrates: It happens when positive feedback works over a shorter distance than negative feedback. Just like wind causing the ridges in the sand. When a grain of sand is first lifted by the wind, it has a high probability of landing on the upsloping nearside of the next ridge, so the positive feedback is 'short-range'. But if the grain manages to

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[65] **Alan Turing**. The chemical basis of morphogenesis. *Royal. Soc. of London. Philosophical Transactions.* 237(Series B): 37-72, 1952.

clear the peak of that first ridge, it is inhibited by the shallow angle from landing on the downsloping farside, so the negative feedback is 'long-range'. In a living system, you just need to substitute biochemical reactions for the wind and the sand.

Moses: I'm not sure that I understand.

Socrates: Here's how it works. Suppose that you have a biochemical reaction, in which chemical A is converted to chemical B, and then chemical B is converted to chemical C (Figure 9-2). Now suppose that B speeds up (autocatalyzes) the reaction that converts A to B (green arrow). That's equivalent to positive feedback in a chemical reaction, so B is called an ACTIVATOR. If that was all you had, then if you dumped chemical A into a test tube, along with the enzymes needed to convert it to B and C, the reaction would start slowly, but then would accelerate and rapidly convert all of the A to C due to the positive feedback. Good so far?

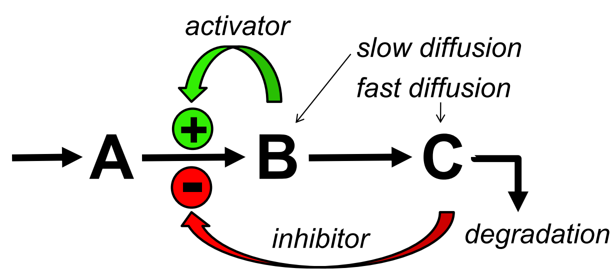

Figure 9-2. Activator-inhibitor system capable of oscillating in time and space. In the chemical reactions, A is converted to B and then B to C. The product B feeds back to further activate the A to B conversion step (positive feedback), but product C feeds back to inhibit the A to B conversion step (negative feedback).

Moses: So far, so good.

Socrates: But now imagine that C has the opposite effect of B and inhibits the conversion of A to B (red arrow). That's equivalent to negative feedback in a chemical reaction, so C is called an INHIBITOR. Now you have B and C competing against each other to accelerate and inhibit, respectively, the conversion of A to B. Sound familiar?

Moses: Sounds like Yin and Yang again. What happens if you mix the chemicals together in a dish?

Socrates: At first, the reaction starts slowly, but then accelerates as A is converted to B and initiates the positive feedback. But after a time delay, as more and more B accumulates and is converted to C, the reaction then slows due to negative feedback, until enough C has degraded for the reaction to speed up again. Then the reaction starts making more B again, which further accelerates the reaction until more B is converted to C and slows the reaction down again. In other words, the rate of the reaction oscillates, going fast, then slow, then fast, then slow, then fast, and so forth. Positive and negative feedback with a time delay, just like the furnace in your home. And if you include one more property of the chemicals, they not only oscillate in time, but also form patterns in space, just like the ridges in the sand.

Moses: What's the extra property?

Socrates: The activator B has to diffuse more slowly that the inhibitor C. Then the slower diffusion of B means that its activating effect is restricted to a shorter range, whereas the faster diffusion of C works over a longer range. There you have it – short-range activation and long-range inhibition, the same conditions that caused the ripples in the sand to form. Now can you guess what happens?

Moses: Let me think. If the reaction randomly starts converting A to B at some random location in the dish, then it will accelerate due to the positive feedback effect of B. But then B starts making C, which feeds back to inhibit the production of B.

Socrates: Very good. So how do the different rates of diffusion of B and C affect things?

Moses: If C diffuses more quickly than B, then the relative amounts of B and C will vary from location to location. In the areas where B is higher, the positive feedback will dominate, causing even more B to be produced. But in the areas where the concentration of C is higher, the production of B will be slowed down by the negative feedback of C. So the dish will develop peaks and troughs in the concentrations of B!

Socrates: Very good, Moses! You can get spots, stripes, spirals, and other patterns depending on the relative amounts of chemicals added (Figure 9-3A). So if you imagine now that the activators and inhibitors are transcription factors that diffuse at different rates to turn on or turn off pigment genes in skin cells, you can explain how tigers and leopards get their stripes and spots, not to mention how those fish swimming below us got their colorful skin patterns. Or you can explain how different body segments form in an embryo (Figure 9-3B). It's exactly what Alan predicted from his early computer models – he called the chemicals "morphogens," because they control shape and pattern. That was 1952, even before the structure of DNA was known.

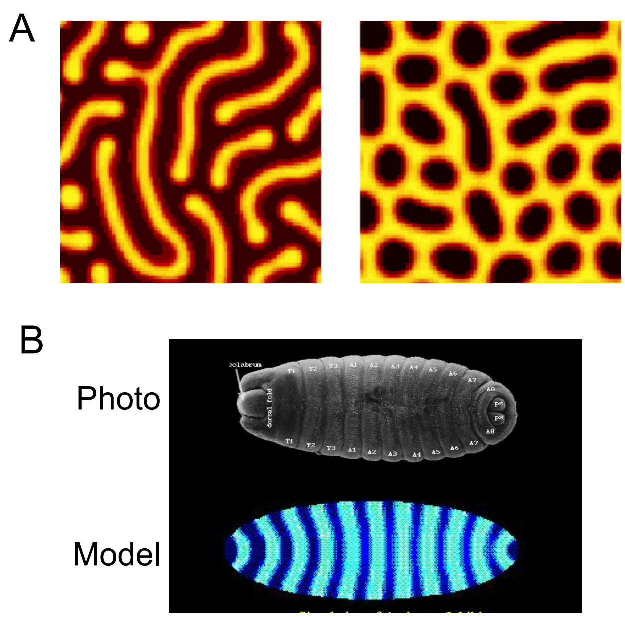

Figure 9-3. A. Spontaneous self-organizing pattern formation by an activator-inhibitor system in which the activator and inhibitor diffuse at different rates. Depending on the properties of the activators and inhibitors, different patterns such as stripes (left) or spots (right) can emerge. **B.** Photograph of the developing body segments in a fruitfly embryo (above) and an activator-inhibitor reaction diffusion model generating a similar self-organizing pattern (below).

Moses: Still, that's just a computer model. How do you know it actually happens in a living organism.

Socrates: How else would a tiger get its stipes or a leopard its spots?

Moses: Maybe in real life the pattern is already encoded in the embryo.

Socrates: You mean that the stripes and spots were already there when the egg was fertilized? Do you really think that if you looked under a microscope, a newly fertilized tiger or leopard egg would already show stripes or spots?

Moses: No, but there might be pre-existing pattern in morphogens that code for the stripes or spots as the embryo develops.

Socrates: If so, then how did they get there? It's kind of like trying to explain the premises in logical reasoning - you may be able to explain one set of premises in terms of a more fundamental set of premises, but then you have to explain where the more fundamental premises came from, ad infinitum. The beauty of Alan's mechanism is that the stripes and spots create themselves almost magically out of an initially homogeneous pattern. That's why they are called *emergent properties*.

Moses: Has the theory been confirmed experimentally?

Socrates: Just as Alan predicted. Boris [66] first demonstrated the phenomenon experimentally in the 1950s with a mixture of chemicals. When he put them in a together in a test tube, the color spontaneously oscillated back and forth between yellow and colorless. In a Petri dish, they produced patterns in space as well (Figure 9-4A &B).

Moses: That must have been a real landmark study for its time!

Socrates: You would think so, but sadly, no one believed poor Boris. He couldn't get his findings published in a peer-reviewed scientific journal. The reviewers all rejected the paper because they thought it violated the Second Law of Thermodynamics and therefore had to be some sort of artifact.

Moses: Why?

Socrates: As we said earlier, the Second Law of Thermodynamics states that the disorder of the universe (its entropy) always increases over time. Which means that, left to their own, things always move from a more ordered, high-grade energy state to a less ordered, low-grade

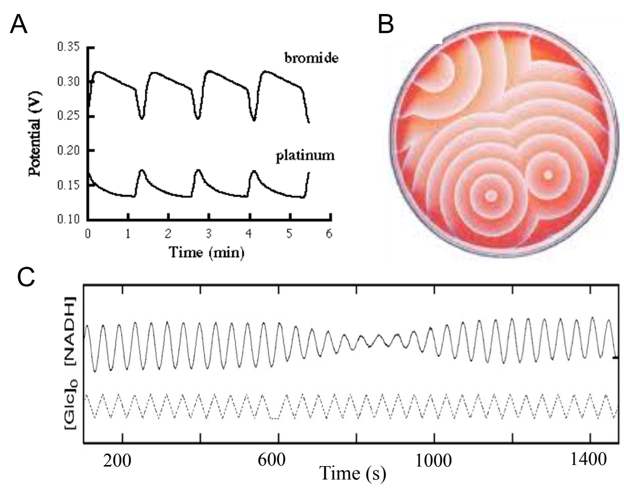

Figure 9-4. Examples of temporal and spatial oscillations in activator-inhibitor reaction diffusion systems. A. BZ reaction oscillations in time. **B.** BZ reaction oscillations in space. **C.** Glycolytic oscillations in yeast.

[66] **Boris Belousov** (1893-1970) was a Soviet chemist/biophysicist who discovered the Belousov–Zhabotinsky reaction (BZ reaction) in the early 1950s. His work initiated the field of modern nonlinear chemical dynamics.

energy state. High-grade energy is like the energy stored in chemical bonds. The lowest grade of energy is heat, the disorganized random vibrations of molecules. So there's a paradox - if you assume that the yellow state of the chemicals is more high-grade than the colorless state, the chemical reaction should proceed from yellow state to colorless state, which increases entropy. But once the chemicals are colorless, they cannot spontaneously return to the yellow high-grade energy state, because that would mean that entropy is spontaneously decreasing, which violates the Second Law of Thermodynamics. Same problem in reverse if you assume that the colorless state is more high-grade than the yellow state.

Moses: So what became of Boris's experiment?

Socrates: He eventually got his paper published in the proceedings of a conference, but it didn't receive much notice. It wasn't until 1961 that a Russian graduate student, Anatol, restudied the reaction sequence and showed that it worked by Alan's predicted theoretical mechanism. Now it's known as the Belousov-Zhabotinsky (BZ) reaction, jointly in their honor.

Moses: So why doesn't the BZ reaction violate the Second Law of Thermodynamics?

Socrates: Because you have to replenish the chemicals to keep the colors changing back and forth. If you don't, the oscillations eventually die out, just as predicted by the Second Law of Thermodynamics. The chemicals that you need to replenish are the ones in the more ordered, high-grade energy state - which means you're adding new high-grade energy to the system. So the energy state is high-grade yellow at first, until the positive feedback by the build-up of the activator suddenly accelerates the reaction, converting the chemicals to the low-grade colorless state. But then the activator gets converted to the inhibitor, which slows the reaction, so that the high-grade chemicals reaccumulate, until the activator builds up sufficiently to overpower the inhibitor again. So as long as you replenish the key high energy chemicals, the reaction will oscillate indefinitely, back and forth between yellow and colorless. During the whole process, the chemical reaction converts the added high-grade energy into heat, so that the entropy of the system increases. And so the laws of thermodynamics are not violated! Meanwhile, the BZ reaction oscillates like a clock for as long as sufficient amounts of high energy chemicals are present.

Moses: Fascinating. That's chemistry, though. Are there examples in biology too?

Socrates: Most definitely. Take glycolysis, for example. It's one of the most basic metabolic pathways that metabolizes glucose to generate energy in the form of ATP for cells to use, from bacteria to mammals. If you mix glycolytic substrates and enzymes together in a test tube under the right conditions, the reaction spontaneously oscillates. It also happens in intact live yeast (Figure 9-4C) and live cells from various mammalian organs. Just like the BZ reaction, it's caused by the feedback between substrates and enzymes acting as activators and inhibitors.

Moses: Is it normal for glycolysis to oscillate in living organisms?

Socrates: It can be, for example, when regulating insulin release. Spontaneous oscillations underlie all of the critical clocks that life depends on, like telling cells when to divide and hearts when to beat! But they need to be regulated, to go faster or slower, or to turn off and on – if cells divide too much, it's cancer, but if they divide too little, it's atrophy.

Moses: And what regulates them?

Socrates: That's the beauty of feedback-driven behaviors. Remember the logistic equation, and how the value of gain factor *a* determined the behavior, from stable to alternating to higher order periods to chaos (Figure 3-2)? The same is true in biological systems. Not only do all of different types of behavior –attractors, repellors, saddles, oscillators, centers, bistable switches, excitable elements and chaos (Figure 5-2) - become possible, but the same system can switch between different types of behaviors by adjusting key parameters. That's why those behaviors are literally the toolbox of life. They can be linked together to produce all sorts of emergent behaviors that turn on and off when needed to support different functions in a living organism.

Moses: Fascinating as your theory about living systems is, there are still a lot of details that remain to be explained. You may be able to dump the right chemicals into a test tube and get spontaneous oscillations in glycolysis, but last time I checked, no one has dumped a bunch of chemicals into a vat and watched a living organism crawl out of the soup!

Socrates: True, the details are admittedly still pretty fuzzy as to how complete living organisms self-assemble. But a complete living organism is also orders of magnitude more complex than a single metabolic pathway like glycolysis. Intact living organisms consist of networks of networks ….and the order in which networks are laid down is very important. In principle, though, if you understand how behaviors like clocks and switches arise from the feedback loops embedded in those networks, you have the basic conceptual tools that you need to figure out how the basic circuits of life work.

Like the egg sitting there waiting to be fertilized, and after a sperm penetrates it, suddenly starts dividing. Or the cells in your heart that stop dividing after birth when the organ has reached the right size. How do those cells know when to stop dividing? Emergent properties are the magic of life, or the mystery of life, if you prefer. And when some new unanticipated emergent property confers a novel survival advantage to a network, then there will be an advantage for the individual components to remain linked together, rather than going it on their own. In a world in which survival depends on competition for limited resources, natural selection will preserve the successful networks, along with its components, and eliminate the others.

Moses: So through these emergent properties, the components gain a survival advantage by being linked together in living system?

Socrates: Exactly, the individual components give up their ability to control their own fate for the greater good of the system – one for all and all for one. It couldn't happen without feedback, that is, ability of individual components to interact reciprocally with each other. That's why single cell organisms evolved into multicellular organisms, and why multicellular organisms evolved into multi-organ organisms like you. And it continues beyond what's goes on inside an individual living organism. It also applies organisms interacting with each other. How else do you think that you humans could have risen to such an exalted position in the animal kingdom, for better or for worse! Think of it – in terms of physical strength, speed, ferocity, etc., you are inferior to almost any animal your own size. In a one-on-one contest, you wouldn't stand a chance against a chimpanzee, let alone a lion, hyena, leopard or bear. Yet you dominate all sorts of ferocious predators. That ability depends on feedback, the ability of individuals to communicate with each other and cooperate flexibly as a group. It is the group, not the individual, that allows you to dominate the rest of the animal kingdom!

Moses: And none of it would be possible without feedback!

Socrates: Precisely. If you think about it, we've really come full circle in linking mathematics to life. Life is full of feedback, which makes oscillations and all the other nonlinear dynamical behaviors possible for living systems, the mathematical toolbox of life! And it all happens spontaneously, no master tool operator required!

Moses: It is uncanny how closely mathematics relates directly to nature and life. It's almost like mathematical principles are not just abstract concepts, but are actually embedded in nature, just waiting for us to discover them! Like imaginary numbers, remember? At first, no one saw any purpose for them, but as it turned out they opened up a whole new set of fundamental building blocks, like spiral attractors/repellers, limit cycle oscillators, centers, excitable elements and so forth.

Socrates: It makes sense from an evolutionary standpoint. If our mathematical abilities evolved as a sense, just like sight or hearing, then perhaps our brains 'sense' mathematical ideas from the way things behave in nature, just like our brains sense the image of a tree from the photons reflecting off it and colliding with our retinas.

Moses: What do you think that Plato would have thought? Could it be that the attractors, repellers, limit cycle oscillators, centers, bistability, excitable elements and strange attractors that serve as the fundamental dynamical building blocks for everything in nature are really the "ideal forms" that he was after?

Socrates: Perhaps the idea would have appealed to him, except for one thing. If Plato's "ideal forms" are supposed to represent perfection, then the mathematics underlying the fundamental dynamical building blocks is certainly not perfect, since it doesn't meet meet the completeness, consistency and decidability criteria, as proven by Kurt's Incompleteness Theorem and Alan's Undecidability of Halting Theorem.

Moses: I guess it depends on your definition of perfection. At least those fundamental dynamical building blocks are completely deterministic, unlike their imperfect realizations in the real world that are always contaminated by nature's randomness, from quantum uncertainty upwards.

Socrates: I wouldn't underestimate the significance of Kurt's and Alan's theorems. Do you remember how Kurt proved his Incompleteness Theorem?

Moses: Wasn't it based on creating the basic arithmetic equivalent of the Liar's Paradox?

Socrates: Correct. In the Liar's Paradox, if you say to me *"This statement is false,"* then I am in a quandary. That kind of statement is incomplete and undecidable because the subject refers to itself in a contradictory way. If the statement is false, then it must be true. But if it's true, then it must be false. Remind you of anything else?

Moses: It sounds like feedback between opposites, kind of like Yin and Yang.

Socrates: Very good, Moses, that's exactly it! When you refer to yourself, you are creating a kind of feedback. Without feedback, the fundamental dynamical building blocks that depend on nonlinearity disappear. Moreover, once you have nonlinearity, things can get very complicated……..you can have more than one possible answer to a question, like the square root of four being either +2 or -2 … or you can have questions with no exact answer, like the Three-Body Problem that so frustrated Sir Isaac, or you can have undecidable questions, like the Liars paradox. In fact, if you think about it, the Liar's Paradox is like a clock. If you were to say to me "This statement is false," then for me to judge its truthfulness, my reasoning would be as follows: if the statement is false, then it must be true … but if the statement is true, then it must be false ….but if the statement is true, then it must be false…..and so on ad infinitum. If the truth were a 'tick', and the falsehood were a 'tock,' then as long as I had the energy to keep trying to decide on the correct answer, you would keep oscillating back and forth, 'tick- tock, tick-tock, tick-tock,' just like a clock. Or like your heart beating, 'lub-dub,' as long as your blood delivers the energy to keep it going. Or like a cell dividing, as long as its metabolism provides enough energy.

Moses: So life depends on the Liar's paradox?

Socrates: In the sense that both life and the Liar's Paradox depend on feedback, the answer is yes. But feedback comes at a cost, namely that life inevitably contains questions with more than one correct answer, questions with no exact answers, and questions with no answers at all. Just like the rabbi said, if a question as simple as the square of four has more than one correct answer, how could life's questions have only a single correct answer? Incidentally, that's another pretty good example synthesizing religious and scientific reasoning for ReliEnce, don't you think?

CHAPTER 10: Bottom-up networks

Moses: I like the idea that life, like other natural phenomenon, might ultimately be explained as a combination of dynamical building blocks – straight-in attractors, straight-out repellers, spiral attractors, spiral repellers, saddles, centers, oscillators, bistability, excitable elements and strange attractors (Figure 5-2) – that self-organize themselves into a living organism. If that's true, then a living organism would just be a fancy machine, a network of dynamical behaviors wired together.

Socrates: Indeed, and without any need to postulate some supernatural component like a soul or mystical life force. Then all you need to do is figure out how the circuit is wired, like you would for a conventional machine.

Moses: Is it a problem, though, that the parts that we're talking about in a living organism are dynamical behaviors, not physical objects like the gears, springs, electronic oscillators and switches in a conventional machine?

Socrates: I don't think that's an issue, since parts in a conventional machine are selected based on their functional behavior too. A timing device is a combination of electronic components wired into a circuit that produces oscillating behavior. A spring is an alloy of metal molecules shaped into a coil to increase its stiffness when stretched. It's those behaviors that are important for the machine, not what the timing devices or springs are made of. Dynamical behaviors in living organisms also arise from real physical objects, namely proteins and other molecules that interact biochemically to generate a particular emergent behavior. A cellular clock is ultimately a network of signaling proteins, and the pattern of the stripes and spots on an animal's skin are real cells directed to express certain genes by the diffusion of real signaling molecules like transcription factors acting as activators and inhibitors.

Moses: I guess that makes sense.

Socrates: But there is one crucial difference.

Moses: What's that?

Socrates: Conventional machines are MADE, not BORN. They require engineers to design, assemble, operate and repair them. Living organisms, on the other hand, have to do all of that on their own.

Moses: True, but isn't that what those dynamical building blocks are for? All the things that they do, they do of their own accord, without requiring any external factors to drive them. That must be the key to how living organisms spontaneously self-assemble and repair themselves without the need for a master engineer directing the process. Those building blocks become the clocks, switches, excitable elements and drivers of spontaneous pattern formation that turn all of those molecular pathways off and on to create a whole that's greater than the sum of the parts, namely a living organism!

Socrates: Even so, to assemble itself, a living machine has to build itself from the bottom-up. That's very different from most conventional machines that are designed from the top down, with a central control center, or "brain," that commands the workflow through a well-defined sequence of steps from input to output (Figure 10-1). The "brain," whether human or an automated control system, utilizes feedback to sense and regulate the flow along the sequence of steps. It's efficient, but obviously not suitable for a self-assembling machine.

Moses: Why not? Aren't we designed in a top-down manner? After all, we depend critically on our brains as the command center for our bodies, don't we?

Socrates: Not really. Our brains are one of our last organs to develop. They don't design, assemble, operate and repair our bodies. Remember, the self-assembly process starts with single fertilized cell. The simplest lifeforms don't even have brains. First, life had to evolve into single cell organisms, then multicellular organisms, and then multi-organ organisms, all before brains even entered the picture. In other words, everything at the bottom had to already be fully capable of operating independently on its own before a brain could even be added to refine and coordinate their functions. That's why most organs can still function without a brain, but a brain can't function without other organs to support it.

Moses: So brains are really just an add-on feature?

Socrates: I'm afraid so. That's not to diminish their importance, of course. Brains evolved as an essential improvement to coordinate a living organism's ability to survive in the world.

Moses: I suppose that makes sense. Then if a top-down strategy isn't feasible, how does a bottom-up strategy work?

Socrates: From the bottom up, naturally.

Moses: Ha-ha, very funny! Talk about restating the obvious.

Socrates: I'll give you a clue. It has to do with our Ying and Yang Axiom.

Moses: Related to feedback again, you mean?

Socrates: Yep. But not just feedback here and there - feedback everywhere. It's feedback on steroids!

Moses: Why?

Socrates: Three reasons. First, a living machine needs feedback to generate the dynamical behaviors like clocks, switches and patterning in order to self-assemble itself. Second, a living machine needs feedback to learn how to survive – to sense the environment, process the input and adjust the output accordingly to increase the odds of surviving long enough to reproduce. Input affects output which affects input which affects output as so forth – that's a feedback loop. You can't learn without feedback. Third, living machines have to be both robust and adaptable, and that also requires feedback.

Moses: The first two make sense. But how does feedback help with the third issue?

Socrates: It has to do with the properties of networks – small world properties in particular.

Moses: What's are small world properties?

Moses: Let's start by comparing top-down and bottom-up strategies. Say you want to build a machine to convert some input *A* through a series of intermediate steps *B, C* and *D* to some desired output *E* (Figure 10-1). A top-down strategy would typically involve a serial process from *A*→*B*→*C*→*D*→*E*, with the workflow through the steps orchestrated by a central control system or "brain". Like an oil refinery that takes crude oil as the input *A* and refines it through a series of steps *B-D* to produce gasoline as the output *E*. That design approach is highly efficient, but it has several disadvantages. First, it's susceptible to failure, since if you cut any one link in the chain, then you can no longer get from *A* to *E*. Second, it is not very adaptable, since it's been designed to accomplish only one task, namely to get you from *A* to *E*.

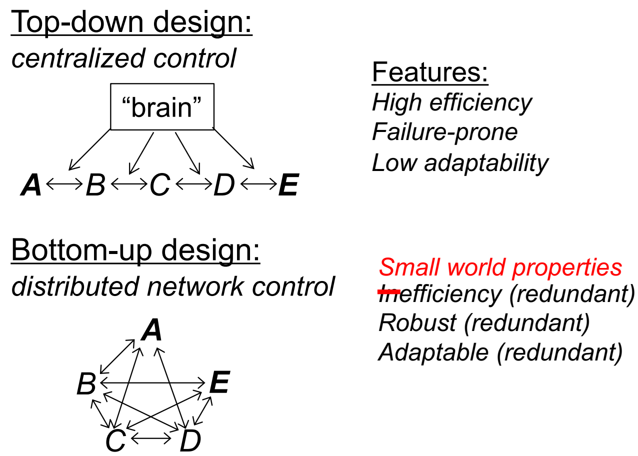

Figure 10-1. Top-down versus bottom-up engineering design.

Moses: I see what you mean. That's not a strategy very well-suited for a living organism, especially when there's no an engineer standing by to fix it if it breaks down.

Socrates: And also not well-suited for a living organism whose day-to-day survival depends on adapting to changing environmental conditions. An oil refinery has only a single task – to make gasoline from crude oil. By contrast, not only does a living organism have to produce its own gasoline-equivalent energy source, called ATP, from different food sources that vary from meal to meal, but it also has to operate many other essential processes in parallel to survive from day to day.

Moses: I see what you mean. A living organism really can't afford to prioritize efficiency over robustness and adaptability. If anything, the engineering priorities have to be reversed. But why is the bottom-up design better in that regard?

Socrates: Because instead of arranging the production steps in series, a bottom-up strategy typically arranges them in parallel. The steps are arranged in a network of interconnected modules, in which *A* is not only directly linked to *B*, but also to *C* and *D*; likewise *B* is linked to *A, C, D* and *E*, and so forth. That creates multiple feedback loops, such as *A*→ *B*→ *C*→ *A*, or *A*→ *C*→ *D*→ *A*, etc. If the link from *A* to *B* should break, you can still get to *E* by bypassing *B* and taking the alternative parallel pathway through *C*. That makes the system inherently less susceptible to failure, i.e. more robust. And it's also adaptable, since the parallel network design has multiple pathways to get you from any point in the system to any other point in a small number of steps. That's the so-called small world feature that allows the input and output to be flexibly repurposed to meet changing demands. And most important, it doesn't require a sophisticated centralized "brain" or control center to keep track of everything going on everywhere. Instead, the control is distributed throughout the network.

Moses: How can it work without a central brain to coordinate overall process?

Socrates: Each module follows its own set of simple rules - a simple "brain" if you will, that tells it how to respond to its neighbors.

Moses: Let me get this straight. The bottom-up machine is a decentralized network of interlinked modules, with all of the modules following simple-minded rules. To me, it sounds like a formula for utter confusion!

Socrates: Not if you choose the right simple rules. When you do, a very sophisticated collective intelligence can emerge from the coordinated interactions between the simple brains. In other words, a whole that's much greater than the sum of the parts.

Moses: An emergent property, right?

Socrates: Exactly, the emergence of a novel collective behavior that bears little resemblance to the behaviors of the individual simple components.

Moses: Have any actual machines been built using a bottom-up approach?

Socrates: Sure. Ever heard of the Ambler versus Genghis contest? [67]

Moses: Sounds like a match between two professional wrestlers.

Socrates: Close, but not quite - it was a walking competition.

Moses: Between Ambler and Genghis?

Socrates: Correct. Ambler was a mobile robot designed by an engineering team at Carnegie-Mellon University. They were funded by the US space program to develop a prototype that could someday be used to explore the terrain of distant planets. In 1990, after a decade of development based on a top-down central control approach, they unveiled their baby - a nineteen foot tall, two ton robot with six crab-like legs and a computer brain that was so heavy it had to sit on the ground connected to the robot's body by a long cable.

Moses: How did Ambler do?

Socrates: Not so well. Ambler spent most of its time computing rather than walking. First, its laser vision surveyed the terrain and converted the images into a symbolic representation. Then, the symbolic representation was analyzed to compute the best trajectory for the next step. Finally, Ambler took a step. It lumbered slowly like a toddler, deliberating between each step in order to assess its next move. But when it

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[67] **Kevin Kelly**. *Out of Control*. Basic Books, 1994.

finally made it across a one hundred foot long courtyard without falling over for the first time, its proud parents were ecstatic!

Moses: At least they got it to work. What about Ambler's competitor? How did Genghis do?

Socrates: Genghis was the brainchild of an MIT Professsor named Rod[68], who designed his robot without a central brain using a bottom-up approach. Genghis also had six legs, but was much smaller – about the size of a football. Each leg had its own microprocessor that followed very simple rules depending on what the other five legs were doing at the time. As Rob described it:

> "There is no central controller which directs the body where to put each foot or how high to lift a leg should there be an obstacle in front of it. Instead, each leg is granted a few simple behaviors and each independently knows what to do under various circumstances. For instance, two basic behaviors can be thought of as *"If I'm a leg and I'm up, put myself down,"* or "*If I'm a leg and I'm forward, put the other five legs back a little."* These processes exist independently, run at all times, and fire whenever the sensory preconditions are true. To create walking then, there just needs to be a sequencing of lifting legs (this is the only instance where any central control is evident). As soon as a leg is raised, it automatically swings itself forward, and also down. But the act of swinging forward triggers all the other legs to move back a little. Since those legs happen to the touching the ground, the body moves forwards."

Once Genghis could walk reliably on a flat surface, other behaviors were added on top - for example, to climb over an object, a whisker was attached in front of each leg to sense the obstacle. But Rob and his team never monkeyed with the fundamental routine, based on the principle that *"If it works, don't mess with it; build a new layer on top of it instead."* In other words, Genghis was completely built from the bottom-up!

Moses: So how did Genghis do?

Socrates: Genghis blew Ambler out of the water! Not only could Genghis walk better and faster, but it was also much more robust and adaptable. For example, if one of Genghis's legs was disabled, the other five did just fine. Not so for Ambler. As a consequence, the space program scrapped the top-down approach with Ambler, and started a brand new program based on Rob's bottom-up approach with Genghis.

Moses: Very impressive. Are there examples of the bottom-up designs in living organisms?

Socrates: Sure. Take a flock of birds, for example. They fly through the air in nearly

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[68] **Rodney Brooks** (b. 1954) is an Australian roboticist, Panasonic Professor of Robotics at MIT and former director of the MIT Computer Science and Artificial Intelligence Laboratory, most known for popularizing the actionist approach to robotics. Quote is from: Brooks, R.A. and Flynn AM. Fast, Cheap and Out Of Control: A Robot Invasion of the Solar System. *Journal of The British Interplanetary Society*, 42: 478-485, 1989.

perfect synchrony without colliding with each other, even when they're being chased by predators. Given the limited computational power of a bird brain, a top-down central control mechanism to calculate individual trajectories to avoid collisions would impossible. But the simple local rule of remaining equidistant from each of your neighbors, below, above and beside you, keeps the flock intact with minimal collisions even when the overall trajectory becomes very complicated.

Moses: How do you know there isn't a lead bird whom everyone else is following using those simple rules? Wouldn't that still be top-down, like an army following the orders of a commanding general?

Socrates: That might work when the flock is flying undisturbed. But what if a predator like a hawk dive bombs into the middle of the flock? The leader in front may not even be aware of the attack, but the birds further back have to adjust their course immediately to avoid the hawk, without colliding with each other, and then reform into a single flock. The lead bird couldn't possible command all that. It's the ability to respond locally that's critical to the flock's integrity.

Moses: I see what you mean.

Socrates: Good. Do the differences between the top-down and bottom-up strategies make sense to you now?

Moses: It seems like the top-down strategy works very efficiently for performing the same repetitive task over and over again, like the oil refinery producing gasoline. But when the task requires a flexible response, like Ambler navigating across unfamiliar terrain or a flock of birds avoiding attack by predators, the bottom-up approach has the advantage. Is that the main message?

Socrates: Yes, very good! And what's particularly interesting is that as the complexity of the task increases, the bottom-up strategy tends to leave the top-down strategy more and more in the dust.

Moses: Now that seems counterintuitive. I would presume as the complexity of the tasks increases, the number of modules required would also increase. And if each module is interconnected to every other module, and there's no centralized brain to coordinate their interactions, how does anything get accomplished? When everything affects everything else, you would think that it would become more and more of a functionally disorganized mess.

Socrates: That is a still a bit of a mystery, and it's precisely why living organisms are so hard to analyze. Perturb one element and it starts a chain reaction that affects everything else. It's like there's a black box separating the input from the output, and inside the black box everything seems to affect everything else. That makes very challenging, if not impossible, to trace a discrete logical pathway linking the input to the output. But that's precisely where the feedback comes in.

Moses: How?

Socrates: Through negative and positive feedback, nodes in a network can influence each other reciprocally either to stabilize a mode of performance, or change to a new mode of performance when the environmental conditions are appropriate. It creates a rich tableau for generating feedback-related emergent properties, like the various clocks, switches and excitable elements that living organisms depend on.

Moses: But it's so complicated! Especially since a living organism isn't just a single network. It's a network of highly interconnected networks. How do you even begin to analyze it?

Socrates: Actually, there's been a lot of progress recently in analyzing highly interconnected networks, including biological networks. It has provided a lot of key insights about how living networks evolve.

Moses: Such as?

Socrates: The idea is to step back and look at a network as a whole, rather than get buried in the limitless details – to see the forest for the trees, so to speak.

Moses: How do you do that?

Socrates: By creating a graph of the network that strips away the details and focuses only on its key elements. The idea originated with Leonhard[69] in the mid-eighteenth century. He wasn't trying to understand living networks, though. He was just trying to solve a parlor game riddle popular among the citizens of his home town, Königsberg, Germany.

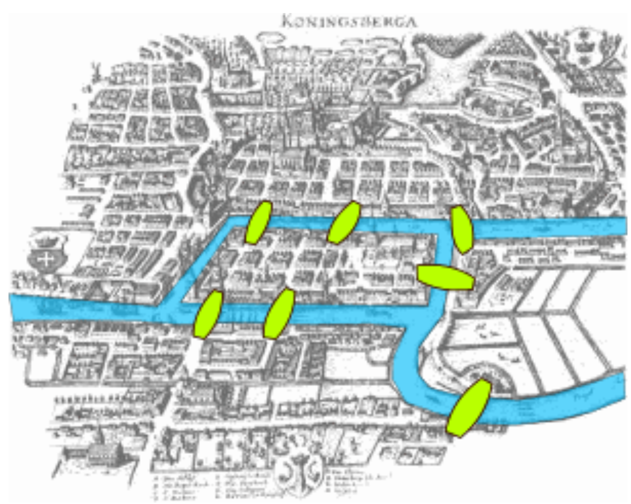

Figure 10-2. Map of Konigsberg, Germany, circa 1700, showing the Pregel River (blue) with its seven bridges (green) connecting four land masses.

Moses: What was the riddle?

Socrates: The puzzle had to do with the city's geography. Königsberg was situated between branches of the Pregel River. Kneiphof Island was at the center of town, with seven bridges connecting it to three outlying land masses (Figure 10-2). The question was, could you start from Kneiphof Island, walk through all the surrounding sections, and return to your starting point by crossing each bridge only once?

[69] **Leonhard Euler** (1707-1783), the Swiss mathematician, physicist, astronomer, logician and engineer, made important and influential discoveries in many branches of mathematics, such as infinitesimal calculus, graph theory, topology and analytic number theory. He is also known for his work in mechanics, fluid dynamics, optics, astronomy, and music theory. Euler is held to be one of the greatest in history and is also widely considered to be the most prolific mathematician of all time.

Moses: And I take it that he solved it, right?

Socrates: Correct. He drew a graph in which he represented each land area as a node, and each bridge as a link between adjacent nodes. Then the solution became obvious – if you can only use each link (bridge) once, then an even number of nodes requires an even number of links to return to the same node, and vice versa for an odd number of nodes. For example, if there are two nodes, North and South, then to go from North to South requires one link (bridge #1), and to return from South to North by a different pathway requires a second link (bridge #2). If there's a third bridge to cross, then you can't get back to your original starting location without crossing one of the three bridges twice. Since Königsberg had four nodes and seven links, the correct answer to the riddle was 'No', a citizen could not visit all four areas and return to their original starting point by using each bridge only once. Simple reasoning, with which Leonhard invented a whole new branch of mathematics called graph theory.

Moses: Very clever. The citizens of Königsberg must have been very flattered to have such an illustrious mathematician invent a whole new branch of mathematics to solve their little parlor game.

Socrates: No doubt they were! And it did solve a real world problem, even if a trivial one. That's more than you can say about some branches of mathematics, that were developed with no real world applications in mind, not even trivial ones. Like when Alan tackled the decidability of arithmetic problem by conceiving of the Turing machine - a totally esoteric problem which no one at the time envisioned had any real world applications. But a few decades later, it turned out to be the key for Alan and others to invent modern computers, which went on to transform human culture!

Moses: So what happened with this graph theory? How long before it solved something more substantial than the Königsberg puzzle?

Socrates: It took a few hundred years, actually. The theory was formally developed by later mathematicians, but didn't really have any important applications to real world problems until the twentieth century. That's when it caught the attention of social scientists.

Moses: Why?

Socrates: Because graph theory turns out to be very useful for tracking how information flows through complex social networks, which tend to be densely interconnected. By representing people abstractly as "nodes", and the interactions between them as "links" or "edges", graph theory gives you a ten thousand foot view of how information flows through society. The same idea can be applied to simple or complex networks, anywhere from molecules to societies. For example, even a simple physical object, like an ice cube, can be represented as a network. The water molecules are the nodes and the electrostatic forces between the positively-charged end of one water molecule and the negatively-charged end of its neighbor are the links (or edges) that hold the ice cube into an ordered lattice (Figure 10-3, left panel). In this case you get a "large world" network, in which information flows locally from nearest neighbor to nearest neighbor.

In other words, it takes a large number of steps for the information to get from one end of the ice cube to the other. For example, if you put the ice cube on a hot plate, the water molecules on the bottom layer absorb the heat first and start to vibrate. Their vibrations cause the next layer of water molecules to vibrate, and so forth, from layer to layer until the heat finally reaches the topmost layer. That's why the ice cube melts from the bottom up. The average path length, defined as the number of molecular steps required for heat to be transferred from the bottom layer to the top layer is large. However, social networks are different. They have "small world" properties.

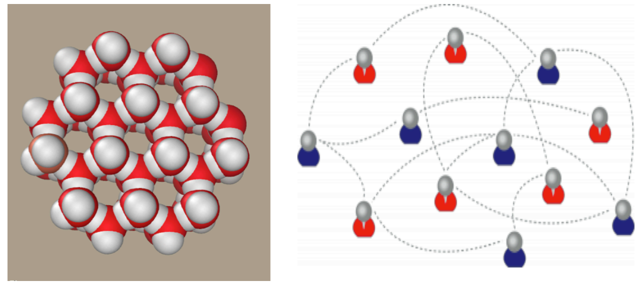

Figure 10-3. Left panel. Ice as a large world network of nodes (water molecules) connected to their immediate neighbors by links (electrostatic forces between positive red and negative gray charges). **Right panel.** Social friendship network with long-range connections creating small-world properties.

Moses: You mean that you're finally going to tell me what that means?

Socrates: Of course. Unlike water molecules in an ice cube, social networks can have long range connections between nodes, which allows information to leapfrog over long distances (Figure 10-3, right panel). That creates the "small world" feature that I mentioned before.

Moses: Sort of like the "six degrees of separation" idea?

Socrates: Exactly. In fact, it was John's play "Six Degrees of Separation"[70] that popularized the idea. One of the characters in the play says:

> "I read somewhere that everybody on this planet is separated by only six other people. Six degrees of separation between us and everyone else on this planet. The President of the United States, a gondolier in Venice, just fill in the names. I find it A) extremely comforting that we're so close, and B) like Chinese water torture that we're so close because you have to find the right six people to make the right connection... I am bound to everyone on this planet by a trail of six people."

Moses: Isn't that also similar to the Kevin Bacon game?

Socrates: Yes, same idea. Kevin never acted in the play, as far as I know, but he once remarked during an interview that he had worked either with every actor in Hollywood,

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[70] *Six Degrees of Separation* is a play written by American playwright **John Guare** (b. 1938) that premiered in 1990. The play was nominated for the Pulitzer Prize for Drama and the Tony Award for Best Play.

or else with someone who had worked with them. His comment inspired three college students to invent the Kevin Bacon game. The object was to guess any actor's "Bacon number" – that is, the number of actors separating them from a Kevin Bacon movie. For example, Elvis Presley has a Bacon number of two, since Elvis was in *Change of Habit* (1969) with Edward Asner, and Edward Asner was in *JFK* (1991) with Kevin Bacon. Edward's Bacon number is therefore one. The largest Bacon number is eight, so every working actor in the movie industry is connected by at most 8 steps. Kevin thought that the college students were making fun of him, and was annoyed at first. But later, he embraced the idea and even started a foundation based on the concept, to emphasize the interconnectedness of human society.

Moses: So a playwright and three college students figured this out?

Socrates: Not exactly. The play and the game were both originally inspired by a 1950s sociology experiment that Stanley[71] designed. He wanted to estimate the probability of two randomly selected people knowing each other. So he randomly chose people from Omaha or Wichita and instructed them to mail packages to another group of randomly-selected people in Boston. But they could only mail the packet directly to the person in Boston only if they knew them on a first name basis. If not, they had to mail the packet to someone else whom they thought might know the Bostonian on a first name basis, and ask them to mail the packet. And if that person also didn't actually know the Bostonian on a first name basis, they mailed the packet to someone whom they thought might know them on a first name basis, etc., until the letter arrived (or not) to the Bostonian in question. The question was how many mailings would it take for the packet to arrive at its destination. Most of his colleagues doubted that the packages would arrive at all. However, they were surprised to find out that, on average, only six mailings were required, because of long range connections. That is, the person in Omaha or Wichita had a friend or a friend-of-a-friend who lived in Boston, and that person in Boston had a friend or a friend-of-a-friend who knew the person in question. That's how long range connections make for efficient information flow, even in very large complex networks. Since then, many other examples have been described, and not just in social interactions.

Moses: Like what?

Socrates: How about flying from Omaha to Boston on a commercial airline? If there was no direct flight from Omaha to Boston, you'd be crazy to take the shortest route geographically, going from small airport to small airport until you reached Boston. Instead, you'd fly to a large city like Chicago, and then take a direct flight from Chicago to Boston. Even though the distance is longer, it's a heck of a lot quicker. What's

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[71] **Stanley Milgram** (1933-1984), an American social psychologist. After earning a PhD in social psychology from Harvard University, he taught at Yale, Harvard, and then for most of his career as a professor at the City University of New York Graduate Center until his death in 1984. His small-world experiment, while at Harvard, led researchers to analyze the degree of connectedness, including the six degrees of separation concept.

amazing is how few long distance connections are needed to create the small world effect in a network. Steve and Duncan[72] figured out how to analyze it mathematically. If a large number of nodes are connected to each other locally, they form a cluster. If one of those nodes in that cluster has a long range connection to another cluster, then the shortest path between any two nodes in both clusters becomes very short. For example, to get from node *a* in Cluster O (for Omaha) to node *b* in Cluster B (for Boston), you go from node *a* to the hub node of Cluster O, to the hub node of Cluster B, and then to node *b*. Voilá, you're there in only 3 steps!

Moses: This is all very interesting, but we seem to be getting a bit off the track. What do social networks and airplane routes have to do with biology?

Socrates: We're getting there. The next real breakthrough came with the Internet and the World Wide Web.

Moses: Another social network?

Socrates: Yes, but a very useful one, since it was created in the early 1980s, and the history of all of its nodes (websites) and links (between websites) has been preserved.

Moses: I still don't see the connection.

Socrates: The internet is like a microcosm for Darwinian evolution, but instead of competing for reproductive success, the competition is for market share or popularity, with only the most successful websites surviving. And what's most intriguing about the Internet is that it has no central command center. No single organization controls it – yet despite its explosive growth, it is remarkably dependable and robust. It has evolved the ability to defend itself against viruses, to develop secure communication allowing safe financial transactions, to search efficiently for information among an ever-expanding number of websites, and so forth. So how does this all work without a mechanism for centralized oversight?

Moses: That is pretty amazing, actually. Pretty much anyone can launch a website. And as a result, it's attacked all the time by hackers. Yet it's incredibly reliable, and rarely crashes on a large scale.

Socrates: That's because each new cyber-attack spawns a new defensive response by those who have a vested interest in its continuing to function, minimizing the disruption. The same way a living organism's immune system neutralizes a virus or bacterium with antibodies. Like I said, survival of the fittest.

Moses: So do you mean that the Internet has evolved like a living organism, driven by natural selection and survival of the fittest?

Socrates: That's exactly what László [73] and his colleagues discovered – that the way that

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[72] **Steven Strogatz** (b. 1959), an American mathematician and the Jacob Gould Schurman Professor of Applied Mathematics at Cornell University; **Duncan Watts** (b. 1971) is a sociologist and a Professor at the University of Pennsylvania.

[73] **Albert-László Barabási** PhD. (b. 1967), Distinguished Professor and Director of Northeastern University's Center for Complex Network Research (CCNR). He introduced in 1999 the concept of scale-

the nodes and links are organized is the same for the internet as it is in many more fundamental biological networks. They all share a similar organizational structure, called a scale-free network architecture.

Moses: Doesn't scale-free refer to something that looks the same, whether you are looking at it close up or from far away? Like a coastline, whose contours look similar from close up or far away, just repeating themselves at larger scales (Figure 10-4).

Socrates: Yes, that's correct, and it's the same for a scale-free network. If you look at how the links are distributed among the nodes, the same fractal structure keeps repeating itself, like the branches of the snowflake. It's related to the conditions under which a network grows. If the network evolves under selective pressures, then the scale-free structure emerges naturally.

Figure 10-4. Fractal nature of coastlines illustrated by the southern coast of England showing self-similar contours at 3 different magnifications.

Moses: How?

Socrates: Imagine that you have a bunch of nodes and links, and you connect the nodes together by randomly assigning links to them. Some of the nodes would end up with more than the average number of links, and some less. If the links were distributed on a purely random basis, the number of links per node would follow a normal (Gaussian) distribution (Figure 10-5, red curve). If the average node had two links, for example, then the probability of a node having twenty links would be extremely low. In other words, highly connected nodes with many links would be very rare.

Moses: Okay, so far so good.

Socrates: Next, imagine that the network is growing, so that new nodes and links are being added all the time. Like when the Internet started to become popular, with people adding new websites and linking them to other websites. If you were one of the original websites, you would have been around longer and randomly acquired more links than recently arrived nodes. That is, the older websites would tend to be more highly connected than the younger ones. The oldest websites, with the most links, would become the hub nodes of the network. Since they would be likely to include long range as well as short range connections, the network as a whole would start to exhibit small world properties. Statistically, the number of links per node would now follow an

free networks and proposed the Barabási–Albert model to explain their widespread emergence in natural, technological and social systems, from the cellular telephone to the World Wide Web or online communities and later for biological systems.

exponential distribution, instead of a normal distribution (Figure 10-5, green curve).

Moses: Makes sense so far.

Socrates: Now imagine one additional feature of this growing network – a Darwinian "survival of the fittest" factor. Suppose that when new nodes and links are added to the network, they prefer to become linked to already highly-connected nodes. For example, if you launched a new website, then you'd probably prefer to link to *Google.com* than link with me at *SocratesTheSeaLion.com*. When new nodes prefer to form links with already highly connected hub nodes, it's called preferential attachment. It results in a positive feedback loop such that the already highly-connected hub nodes become even more highly connected. The rich get richer, so to speak. Statistically, the number of links per node now follows a power law distribution (Figure 10-5, purple curve), which is typical for scale-free processes. Whether you look at nodes with one, two, three, four, etc., links, or nodes with ten, twenty, thirty, forty, etc., links, the distribution looks the same. That is, no matter what scale you look at, there will always be some very highly-connected nodes with many more links that the average node.

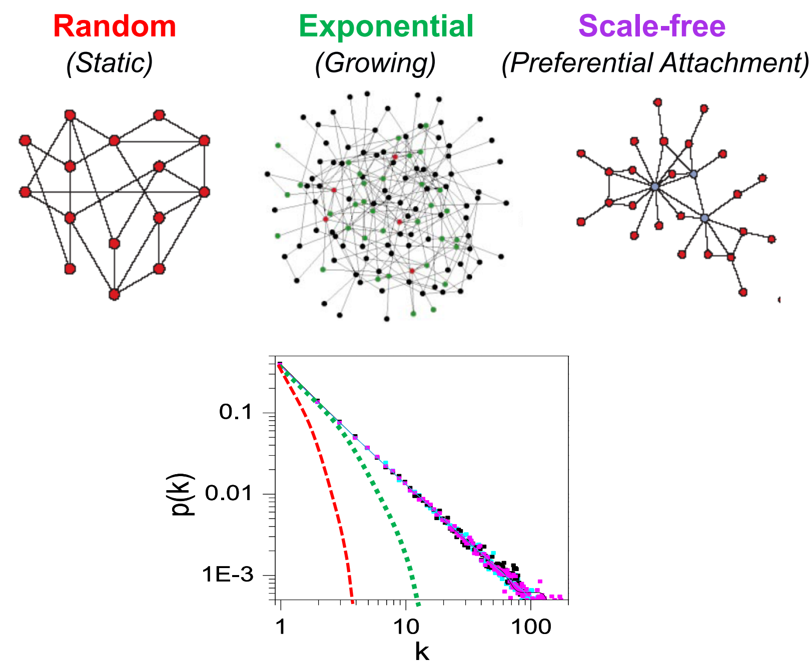

Figure 10-5. Networks in which links (lines) have been distributed randomly to nodes (circles) under static conditions, growing conditions and growing with preferential attachment to already highly connected nodes. Graph shows the probability p(k) of a node having k links (for k=1, 2, 3,.. etc) for the 3 cases, indicating normal (red), exponential (green) and scale-free (purple) distributions respectively.

Moses: So let me get this straight. First, the Internet began with nodes that randomly made connections to other nodes. Second, the Internet continued to grow, adding new nodes and links all the time. Third, the new nodes preferred to link to already established, highly-connected nodes. So you have these three properties - random interactions, growth and preferential attachment - that "evolved" to produce the Internet. Without any central control system to tell which nodes to link with which nodes, but just by randomly adding new nodes and links. And somehow, this process self-organizes itself into a very robust, dependable system. I am beginning to see how you and László might think that this is relevant to biology.

Socrates: It is biology - social biology to be specific.

Moses: Very intriguing, I admit. But still a long way from fundamental biology. How does it apply to basic biological processes, like genes, proteins or metabolism?

Socrates: Because you can represent them as networks too.

Moses: How?

Socrates. Take metabolism as an example. All living things, even simple bacteria, need energy to carry out various functions, such as synthesizing DNA, proteins, lipids and carbohydrates and performing specialized functions that vary from cell type to cell type. Metabolism works by converting chemicals called metabolites from one form (the substrate) into another form (the product), using specialized proteins called enzymes to catalyze the chemical reactions. Thanks to the wonders of modern biochemistry, we have a pretty complete knowledge of all the biochemical pathways that a bacteria like *E. Coli* can use convert nutrients into the metabolites. But it's pretty complicated – in the case of *E. Coli,* there are 778 metabolites and 5,763 enzymes. To simplify it, you can think of each of the metabolites as a node, and each of the enzymes that converts one metabolite to another as a link (Figure 10-6). When László and his colleagues analyzed how the links are distributed between the nodes, they discovered that the distribution is scale-free, the same as the Internet, social networks and airplane routes.

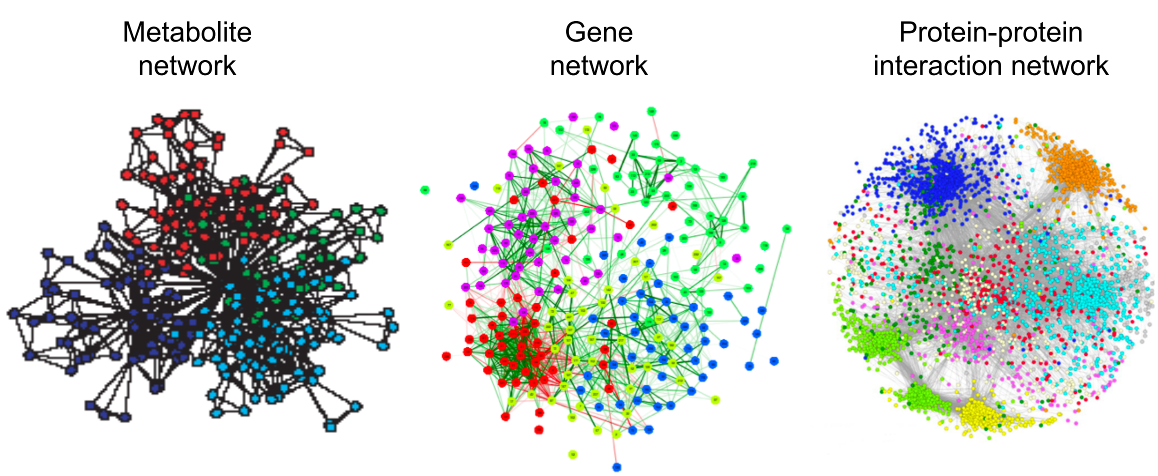

Figure 10-6. Examples of metabolic, gene co-expression and protein-protein interaction networks with small world scale-free properties. Circles are nodes, lines are links, colors indicate different modules.

Moses: How do you know it's not just coincidence?

Socrates: That's certainly possible. But what's amazing is that it's not just true for metabolic networks. If you look at the way genes interact with each other, they also form a network. Each gene in an organism's genome is designed to carry out some aspect of cellular function, such as coding for a structural protein or a metabolic enzyme or turning other genes on or off. In graph theory, each gene is represented as a node, and each interaction between two genes as a link. And if you analyze the statistics, gene expression networks also typically show a scale-free structure (Figure 10-6).

Moses: What else?

Socrates: Proteins. Proteins interact with other proteins, and those interactions play a key role in living cells. Many proteins in a living cell operate in multi-protein complexes. Structural proteins cement the complex together and anchor it in the proper location in the cell; signaling proteins switch the function of the protein complex off and on; metabolic proteins provide energy for the protein complex to perform its functions, etc. If you think of each protein as a node and each protein-protein interaction as a link, and analyze the statistics, protein networks also show evidence of scale-free structure (Figure 10-6).

So it could be that this is all just a big coincidence. But it definitely makes you wonder!

Moses: I doubt it's a coincidence, because you've already shown that there are big advantages for living networks to be densely interconnected. Like having redundant pathways to get to the same endpoint in case a preferred pathway is blocked, to promote robustness, and having many potential feedback loops to promote emergent properties.

Socrates: Like we said, a densely interconnected network is inherently much less prone to failure, since there is always an alternate pathway to reach a given destination. Laszlo and his colleagues found that scale-free networks can also tolerate a lot of random damage to their nodes and links before the system fails globally. If you attack a scale-free network by randomly destroying nodes or links, you typically have to destroy 80% of them before the system fails globally. Redundancy makes scale-free networks very robust, even without any centralized command.

Moses: So what about adaptability and efficiency? How do scale-free networks promote those features in living systems?

Socrates: That's where their small-world properties come in.

Moses: You mean that metabolites, genes and proteins are all playing the Kevin Bacon game? How does the 'six degrees of separation' factor relate to molecules?

Socrates: I'll give you an example. Imagine one of the *E. Coli* bacteria that is replicating in your colon right now. One of the 768 vital metabolites that *E. Coli* synthesizes is uridine, which is needed to synthesize DNA. If the *E. Coli* doesn't have enough uridine to make DNA, then it can't replicate. Now imagine that instead of a highly interconnected network (Figure 10-7A), the metabolic pathway of *E. Coli* were arranged serially in a linear sequence (Figure 10-7B). If you drank some juice containing glucose, then it might take the *E. Coli* in your gut only a few metabolic steps to convert the glucose to the uridine needed to synthesize DNA. But suppose the next time you get thirsty, you drink a beer instead. Now the *E. Coli* has to synthesize uridine from ethanol instead of glucose. If this takes a large number of metabolic steps, it will be slow, energetically costly, and inefficient, and therefore costly to survival. In other words, the bacterium would waste a lot of time and energy converting ethanol to uridine, putting it at a disadvantage.

However, the long-range connections in a small-world network take care of this problem (Figure 10-7C). The real metabolic network of *E. Coli* is arranged in a scale-free network, and it is easy to switch from glucose to ethanol as the fuel for uridine or any other essential metabolite, since the average number of chemical reactions needed to convert one metabolite to another is only 3.2 steps. The ethanol is converted to the

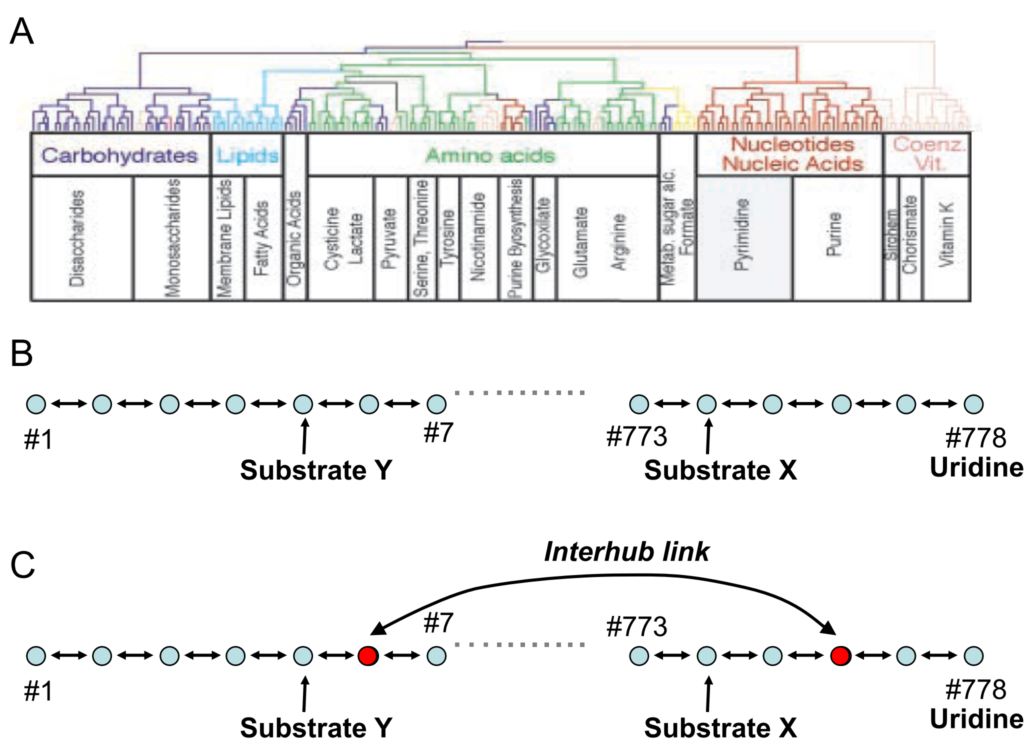

Figure 10-7. Metabolism of the bacterium *E. Coli*. A. Network representation of *E. Coli* metabolism, with links (colored lines at top) connecting the metabolic modules. **B & C.** Hypothetical situation where *E. Coli* metabolism is linear without (B) or with long-range interhub links conferring small world effects (C).

hub metabolite in its cluster, that's the first step. Then that hub metabolite is converted to the hub metabolite of the uridine cluster, that's the second step. And then that hub metabolite is converted to uridine, that's the third step. Only a few steps, whether starting from glucose or ethanol, and our *E. Coli* bacteria is now happily and efficiently making DNA from either metabolite and replicating away. Less energy wasted translates to better fitness, better adaptability and better survival when environmental conditions are constantly changing.

Moses: On the other hand, maintaining all the redundant pathways must be very inefficient compared to maintaining a single pathway. Compared to a linear chain, it seems that a scale-free network has to sacrifice a lot of efficiency.

Socrates: It's true that a scale-free network is generally less efficient than a linear chain when the operating conditions are always the same. But if the environment is constantly changing and the network has to adapt to those changes, then all bets are off. Think of the *E. Coli* when you decided to switch from a soft drink to a beer? If *E. Coli's* metabolism had a linear serial design, then it could be much more energetically costly to go through a hundreds of extra steps to convert ethanol to pyruvate. But with small world properties, the redundancy makes you more rather than less efficient in adapting to changing environmental conditions, since only 3 steps are required. Coupled with the robustness and adaptability of small world scale-free networks, it's a no-brainer.

CHAPTER 11: Learning and Intelligence

Moses: It's pretty amazing to think that the life has used the same general principle of random interactions, growth and preferential attachment to evolve the life's simplest components to its most complex, spanning all the way from genes and proteins to social behaviors - all based on densely interconnected small world scale-free networks built from the bottom-up to generate reliable, adaptable and efficient behaviors.

Socrates: Not to mention the extensive feedback loops within the networks that create essential elements like attractors, repellers, switches, oscillators, excitable elements and spontaneous pattern formation that living organisms depend on for cells to divide, organs to form, hearts to beat, brains to send signals and all the other vital functions that help it to learn to survive.

Moses: On the other hand, if that's all there is to it, then why aren't we further along in being able to assemble those biological components to create a living organism, like we can build an electronic device from resistors, capacitors, inductors, and current and voltage sources?

Socrates: Because it's extremely complicated. It's layers upon layers of interlinked networks – genes organized into gene expression networks linked to protein-protein interaction networks, linked to metabolite networks, linked to organellar networks, all linked into the cellular network, then the cells linked to tissue networks, tissues linked to specialized organ networks, and finally everything integrated into the whole organism. And both within and between all of the layers, feedback is everywhere, with everything affecting everything else. That makes the internal logic very opaque, even for a single cell organism.

Moses: Do you think we'll ever figure it out?

Socrates: Not without some new tools.

Moses: What kind of tools?

Socrates: I call it "black box calculus".

Moses: What's that?

Socrates: Like I said, it hasn't been invented yet.

Moses: I see. Why "black box calculus"?

Socrates: All major advances in science require new tools. Take classical physics, for example. To start the ball rolling, Sir Isaac had to invent a completely new branch of mathematics – calculus – to formulate his Laws of Motion. That's what allowed him to solve the two body problem and predict the elliptical orbit of the earth around the sun plus all of the other stuff. All of classical and modern physics, chemistry and even numerical computation since then depends on calculus.

Living systems, on the other hand, are inherently more resistant to logical and mathematical reasoning because of their complexity. You have an input, which is a collection of genes (the genotype) at one end, and an output, which is an individual organism (the phenotype) at the other end. And in between are all of those densely interconnected layers of biological networks - a black box in which the input information gets shuffled into so many parallel directions among the various interconnected networks that it's nearly impossible to track a discrete pathway leading step by step from the input to the output. Inside the black box, everything affects everything else. That makes it very hard to make any sense of what's going on. Yet somehow the black box manages to take a genotype in a fertilized egg and convert it into a functioning phenotype in a living organism. The way I see it, the major stumbling block right now is the lack of a rigorous method to calculate what's going on inside the black box - ergo "black box calculus." You need a new Sir Isaac to come along to show the way.

Moses: What if new Sir Isaac's only come along once in a millennium?

Socrates: Then you'll have a bit of a wait. But remember, as brilliant as he was, Sir Isaac wasn't the only genius capable of inventing calculus. Gottfried[74] independently came up with his own version right around the same time.

Moses: Then hopefully the time is ripe for some brilliant minds to come up with this "black box calculus" that we need to understand life.

Socrates: We shall see.

Moses: Any promising directions?

Socrates: There is one area receiving a lot of attention lately. It might just point the way to how complex networks can learn to adapt and evolve.

Moses: What's that?

Socrates: Machine learning and artificial intelligence (AI). Think about it. Machines are now capable of doing so many things that previously only humans could do. Who would have even imagined 20 years ago that computers would routinely beat humans at games like chess, Go, Shogi, poker and Jeopardy? Or that autonomous self-driving cars, taxis, buses and trucks may soon replace vehicles with human drivers? Or that personal digital assistants can understand, interpret and translate human speech and search vast amounts of information in an instant? Or that computers can outperform radiologists at diagnosing cancer on MRI and CT scans, or compose poems and music that people can't tell are computer-generated?

Moses: So you think that AI might be relevant to how living organisms learn to solve problems in order to survive?

Socrates: There are definitely intriguing parallels. For one thing, AI algorithms based on machine learning don't rely on traditional top-down serial logic like conventional top-

[74] **Gottfried Leibnitz** (1646 - 1716).

down machines. Take language translation, for example. Google spent 10 years trying to make Google Translate using a conventional top-down approach with little success. Then they switched to a machine learning AI approach called deep learning and had a successful version just 9 months later! [75]

Moses: So how is this deep learning AI method different from top-down logical decision-making?

Socrates: Structured logical decision-making follows trees of hard logic, with instructions like "If this, do that." But deep learning AI takes a fundamentally different probabilistic approach. The AI algorithm isn't explicitly programmed to solve a problem in a top-down manner. Instead, it learns from experience.

Moses: Like a toddler learning to walk?

Socrates: In many ways. In fact, deep learning AI was biologically inspired. The term deep learning is shorthand for deep neural networks, based on how neuroscientists think the human brain works. It's more bottom-up than top-down.

Moses: How so?

Socrates: After Alan and the other early pioneers developed the first computers in the 1950s, the question of whether a computer could simulate human intelligence became a hot topic, and so the field of AI was born. As Demis and his colleagues describe its early evolution [76]:

> "At the time most AI research was focused on building logical processing systems based on serial computation, an approach inspired in part by the notion that human intelligence involves manipulation of symbolic representations. However, there was a growing sense in some quarters that purely symbolic approaches might be too brittle and inflexible to solve complex real-world problems of the kind that humans routinely handle. Instead, a growing foundation of knowledge about the brain seemed to point in a very different direction, highlighting the role of stochastic and highly parallelized information processing. These operations were directly inspired by single-cell recordings from the mammalian visual cortex that revealed how visual input is filtered and pooled in simple and complex cells in area V1. Moreover, current network architectures replicate the hierarchical organization of mammalian cortical systems, with both convergent and divergent information flow in successive, nested processing layers, following ideas first advanced in early neural network models of visual processing."

Moses: That's a mouthful.

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[75] *The Great AI Awakening* by Gideon Lewis-Kraus, New York Times (December 14, 2006) https://www.nytimes.com/2016/12/14/magazine/the-great-ai-awakening.html
[76] **Demis Hassabis** et al., Neuroscience-Inspired Artificial Intelligence. *Neuron*. 95:245-258, 2017.

Socrates: Let me break it down for you. The first clue came when the early computer scientists pondered Santiago's[77] ink drawings of neurons in the human brain (Figure 11-1). They seemed to show layers of intermediate neurons interposed between the input and output neurons. Later, that idea was substantiated by electrophysiological studies of the visual cortex by David and Torsten [78], who won the 1981 Nobel prize for showing how the visual input signals from the optic nerve were integrated by a succession of deeper layers of neurons. That's where the term neural network comes from.

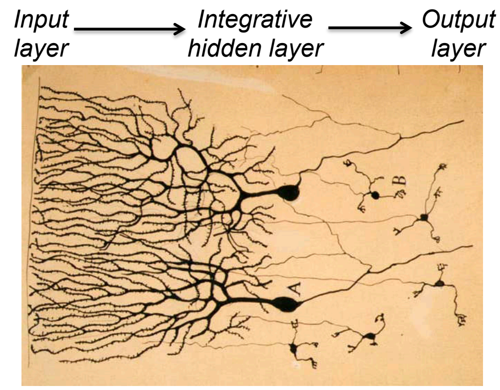

Figure 11-1. Ink drawing of neurons (black) in a region of the human brain.

Moses: Did the neural network approach work?

Socrates: Neural networks generated a lot of interest at the time, but progress really had to wait for more powerful computers. And it also had to wait for big data, since neural networks work best when large datasets are available to train the network. Then in the 1990s, the neural network field really took off. Now deep neural networks can do all sorts of things as well as, if not better than, humans.

Moses: How?

Socrates: Like I said, it's based on how scientists think the brain works. The idea is to create a bunch of software "neurons" and connect them together with "synapses", allowing them to send messages to each other (Figure 11-2). The network of artificial neurons and synapses is then asked to solve a problem, which it attempts to do over and over, each time strengthening the synapses that lead to success

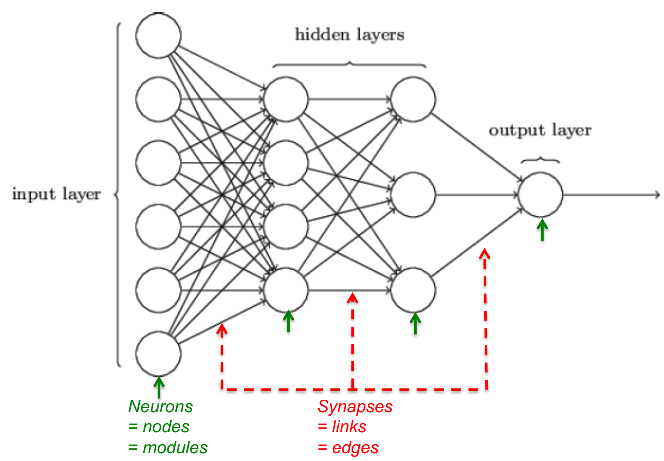

Figure 11-2. Artificial neural network with an input layer, two hidden layers and an output layer of neurons (circles) connected by synapses (arrows).

[77] **Santiago Ramòn y Cahal** (1852-1934), Spanish neuroanatomist considered to be the father of modern neuroscience.

[78] **David Hubel** (1926-2013) and **Torsten Wiesel** (b. 1924) were awarded the 1981 Nobel Prize in Physiology or Medicine for their discoveries concerning information processing in the visual system.

and diminishing those that lead to failure. Eventually, like a toddler learning to walk, it learns how to solve the problem.

Moses: Like what kind of problem?

Socrates: Let me give you an example. There's a collection of handwriting samples called the Modified National Institute of Standards and Technology database, or MNIST database for short. It consists of 60,000 samples of handwritten digits, from 0 to 9 (Figure 11-3). Say that you want to create a neural network to correctly recognize the handwritten digits. How would you start?

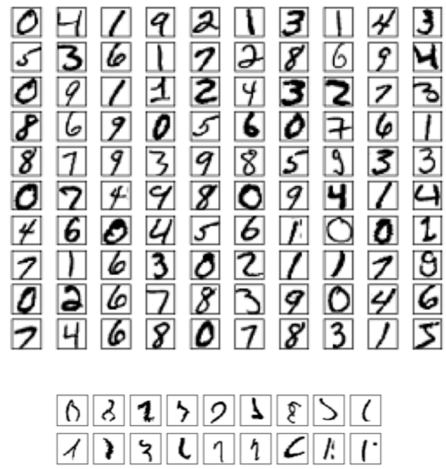

Figure 11-3. Handwritten digits from the MNIST database consisting of 60,000 samples. Some examples of difficult to interpret digits are shown below.

Moses: I suppose that you could use a video camera and image of each handwritten digit sample to use as the input to the neural network algorithm.

Socrates: Very good. For example, if you had a video camera with 28 x 28 pixels, for a total of 784 pixels, then the input to your algorithm would be a sequence of 784 numbers whose grayscale value depends on whether the pixel is light or dark for a particular handwritten digit. Those numbers could be assigned to 784 "input neurons," each representing a specific pixel in the input layer (Figure 11-4). Now what about the output of the algorithm?

Moses: I suppose the output would be the 10 possible values of the handwritten digits, from 0 to 9.

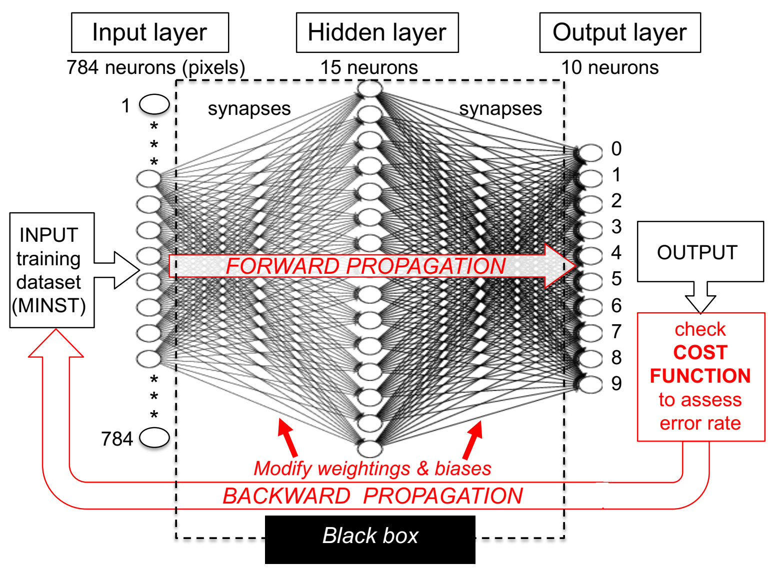

Figure 11-4. Neural network with 1 hidden layer of 15 neurons (black box) designed to learn to recognize handwritten digits from the MNST data base. See text for detailed explanation.

Socrates: Exactly, a layer of 10 "output neurons" from 0 to 9. Now what's in between the input layer and the output layer?

Moses: The proverbial black box?

Socrates: Correct, but can you be a little more specific?

Moses: I suppose that if you're trying to emulate Santiago's drawings, there should be one or more layers of integrative neurons hiding inside the black box.

Socrates: Perfect, you are right on the money! They are the hidden layers, just like the intermediate neurons in Santiago's drawings (Figure 11-1). You can put in as many hidden layers as you want into the black box. By convention, a shallow neural network has only a single hidden layer, whereas a deep neural network has more than one. That's where the term deep learning comes from.

Moses: Then how many hidden layers should we start with?

Socrates: To demonstrate how the principle works, let's keep it simple and start with one (Figure 11-4). Next, you have to decide how many hidden neurons you want the hidden layer to contain.

Moses: I have no idea.

Socrates: It's arbitrary. You just try something and see whether it works.

Moses: Okay. How about fifteen?

Socrates: Perfect, fifteen hidden neurons it is.

Moses: Now what?

Socrates: We connect the neurons with "synapses", so that they can communicate with each other, just like synapses connecting neurons together in the brain.

Moses: How do we know which ones to connect?

Socrates: We don't, so we connect each neuron in the input layer to each neuron in the hidden layer, and each neuron in the hidden layer to each neuron in the output layer.

Moses: That's a lot of connections - 784 x 15 x 10 is over a hundred thousand synapses! With everything so densely interconnected, it's beginning to resemble a biological network.

Socrates: Very astute, Moses! In fact, the neurons and synapses in the neural network play equivalent roles to the nodes and links (edges) in gene, protein or metabolite networks.

Moses: What about the strength of the synapses? Are they all the same?

Socrates: Nope. You start by randomly assigning arbitrary weights and biases to each synapse. That sets the threshold and strength with which each input neuron activates each hidden neuron, and with which each hidden neuron activates each output neuron. Then you let the network figure out how to adjust them to recognize the handwritten digits. Almost like a toddler learning to walk – a high failure rate initially, but practice makes perfect!

Moses: Hmmm…..now you're losing me. How does the network know how to adjust synapses?

Socrates: That's the clever part. You enter the handwritten digit samples into the input layer to activate its neurons according to each pixel's grayscale level. The input neurons then relay those signals through their synapses to the hidden neurons. When a hidden neuron receives a strong enough signal from its input synapses, it becomes activated and transmits its signal through its synapses to the output neurons. Depending on which output neurons are activated, the algorithm then predicts the value of the handwritten digit sample. That's called the forward propagation step (Figure 11-4). Since there are only ten possible outputs, the algorithm should randomly get about 10% right and 90% wrong on the first try.

Moses: Ninety percent wrong is pretty pathetic. How do you train it to do better?

Socrates: The algorithm uses a mathematical formula called a cost function to quantify the average error between its predictions and the actual values of the handwritten digits. Then it performs another mathematical calculation, layer by layer in the reverse direction. It's called the gradient descent method, and estimates how much the weights and biases in each layer should be changed to reduce the cost function and lower the error rate even further [79]. That's the backward propagation step. The cycles of forward and backward propagation steps are repeated over and over again until the cost function reaches a minimum and the error rate is as low as possible.

Moses: What does gradient descent mean?

Socrates: Think of this way. The cost function has a high value (high error rate) for some weight/bias combinations, and a low value (low error rate) for others. If you were to plot the cost function for different weight/bias combinations, it would show a curved surface with peaks and valleys (Figure 11-5). The peaks with high values of the cost function correspond to high error rates, and the valleys with low values of the cost function to low error rates. So far so good?

Moses: I'm following you so far.

Socrates: Good. When you make random guesses for the initial weights and biases, it's not likely to land you at the bottom of a valley with a low error rate, but somewhere else. So the goal is to figure out how to descend from that higher elevation into the nearest valley, where the error rate is much lower. That's why the method is called gradient descent. The mathematical formula tells you how to adjust the weights and biases so that the cost function value descends along the downward gradient, step-by-step, into the nearest valley, rather than climbing upwards to the peak. The steps also have to be the right size to find the valley – the size of the step is called the learning rate.

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[79] **Gradient descent** calculates the derivatives of the cost function with respect to the weights and biases of the synapses to identify how their values can be changed to reduce the cost function. If the derivative (slope) is positive, reducing the weighting value will increase the cost function value, and vice versa. The process starts from the last hidden layer and works backwards layer by layer to the first layer. The changed values are then run again in the forward direction to determine that the cost function has been reduced. The cycle is repeated until the cost function reaches a minimum value and further changes to the weights and biases make it increase.

Moses: Very clever. I take it that the algorithm just keeps cycling between the forward and backward propagation steps using gradient descent to march down into the valley and achieve the lowest error rate. In other words, the forward and backward propagation steps constitute a feedback loop!

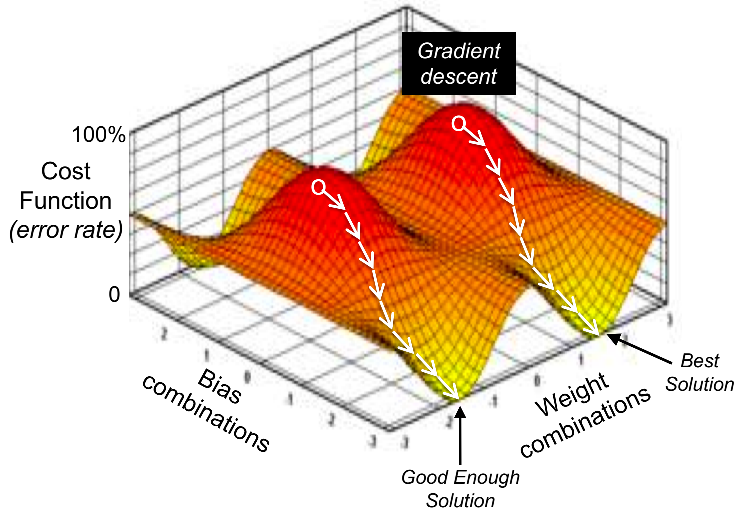

Figure 11-5. Gradient descent mathematically calculates how to alter the weights and biases to reduce the cost function and descend into the nearest valley (arrows), which can be different depending on the initial random starting point (circles). The deepest valley is the optimal solution, but other valleys can exist and may be good enough for the task at hand.

Socrates: It makes sense, doesn't it? To learn a task, you need some kind of feedback to tell you how to adjust your behavior to complete the task successfully, whether you're a machine or a living organism.

Moses: Still, if it starts with 90% error, that's a long way to go. How well does it do?

Socrates: Quite well. With a single hidden layer, the error rate typically falls to around 5% [80].

Moses: That's pretty impressive! How many cycles between the forward and backward propagation steps does it take?

Socrates: The gradient descent method is remarkably efficient when the learning rate is chosen properly - it only takes a few cycles to get below 10% (Figure 11-6A). The feedback loop is critical.

Moses: What happens without the feedback loop?

Socrates: If you remove the backward propagation step and try to find a combination of weightings by trial and error, you'd be lucky to ever find a good enough solution with less than a 10% error rate! When I tried it, the lowest error rate that I achieved was 80% (Figure 11-6B), and that was after a million guesses! Not a single combination produced an error rate anywhere close to 10%, so finally I gave up.

[80] See **MNIST** website: http://yann.lecun.com/exdb/mnist/

Moses: I guess it's not surprising when you have over a hundred thousand synapses to assign weights and biases to. You'd have to be very lucky to pick the right combination by chance – like winning the lottery.

Socrates: Much worse odds than winning the lottery, actually! From the distribution of error rates after a million trials (Figure 11-6A), you can estimate statistically the odds of randomly picking a combination of weightings that gives an error rate under 10%. The odds are less than one in 10^{80} - that's a one followed by eighty zeros. Does that number ring a bell?

Moses: Not particularly, except that it's extremely large.

Socrates: According to physicists, 10^{80} is the estimated number of atoms in the observable universe! So the odds of picking that combination of weightings randomly are much worse finding a needle in a haystack – it's like finding one particular atom in the whole universe!

Moses: I see your point. But is a 5% error rate the best that a neural network algorithm can achieve? I'll bet that any reasonably literate human could do better than that.

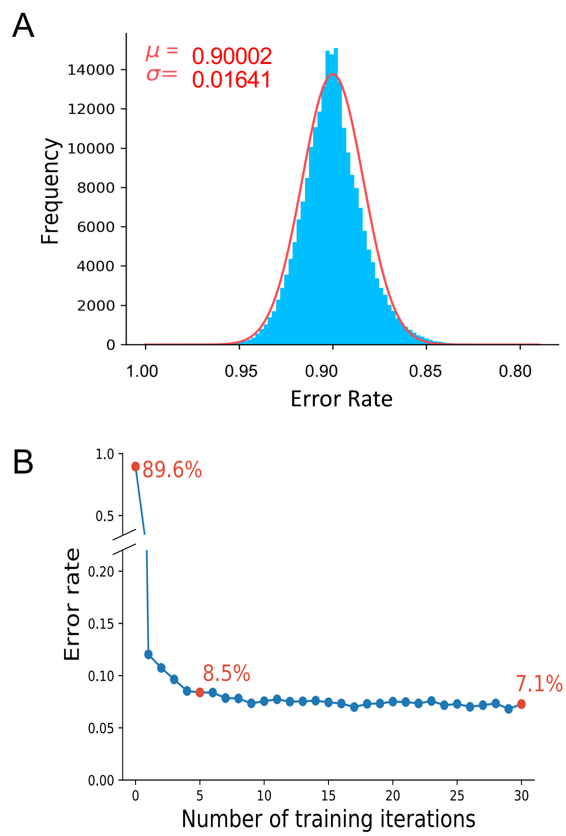

Figure 11-6. Training efficiency of the neural network in Figure 11-4 with 1 hidden layer, without and with backward propagation. **A.** With just forward propagation, the lowest error rate achieved after 1,000,000 randomly selected initial values of weights and biases was >80%. **B.** With both forward and backward propagation, a set of randomly selected initial values gave an error rate of 89.6%, which decreased to 8.5% after only 5 iterations and 7.1% after 30 iterations using gradient descent.

Socrates: Five percent error is about the best the algorithm can do with a single hidden layer. But you can achieve well under 5% with multiple hidden layers. And with other mathematical tricks like convolutional neural networks (CNN), the error rate is well below 1%. That's the same or better than humans considering that some of the handwritten digits are quite ambiguous (Figure 11-3).

Moses: Pretty amazing! But how do you know it works on other handwritten digit samples besides the ones it was trained on?

Socrates: Because you don't use all of the sixty thousand handwritten digit samples to train the network. For example, if you use fifty thousand samples to train the network, then you can reserve the remaining ten thousand to test the error rate on samples that the algorithm has never seen before.

Moses: Very clever. But one thing still confuses me.

Socrates: What's that?

Moses: If the rules for finding the correct weights and biases are all completely specified by mathematical equations, why do you say that the hidden layer is a black box? The hidden neurons are just summing the inputs from the neurons in the previous layer, from the bottom up. What's the mystery?

Socrates: An excellent question. The logic behind the computational method is very clear, I agree. But what's intriguing is that once the neural network has been trained to solve a problem, the logical flow connecting the input to the output is pretty opaque.

Moses: Why?

Socrates: Here's what's going on. Each hidden neuron has a different set of weights from its inputs. What those different weightings are doing is detecting some specific feature of the handwritten digit image. Some hidden neurons may be detecting recognizable features, such as vertical lines, horizontal lines, diagonal lines, crossing lines, or circles. But some neurons may be detecting features that don't make any obvious sense to us – patterns that seem meaningless to us, but nevertheless are highly predictive for the trained algorithm to be able to identify the image correctly. And if it's a deep learning algorithm with many hidden layers, the hidden neurons in each deeper layer are remixing the features from the neurons in shallower layers into even more complex features that may make even less intuitive sense to you or me. It's a bottom-up process, with more and more complex features being generated progressively from hidden layer to hidden layer. That's what gives the deep neural network its power of discrimination to predict the correct output.

Moses: So what you saying is that because the algorithm learns empirically, it ends up selecting features that work empirically, whether or not they make any sense from a human's, or in your case a sea lion's, perspective.

Socrates: That's it in a nutshell. It's not really that different from the network science algorithms used to construct biological networks. Take gene co-expression networks, for example (Figure 10-6). The algorithm places genes that are co-expressed into the same gene module. For example, when the algorithm analyzes twenty thousand genes across many individuals, the expression levels of genes A and B may track each other statistically, whereas gene C is uncorrelated. Then gene A and B would be placed into the same gene module, whereas gene C would be placed into a different gene module. Now here's the surprise. You might expect that the gene modules thus identified would have clearly identifiable functions that intuitively make sense to us. For example, you might expect to find a module of metabolic genes, a module of cell division genes, a module of signaling genes, a module of structural genes, and so forth, similar to a business that's organized into divisions with specific functions, like purchasing, production, sales, advertising, human resources.

Moses: But that's not what you get?

Socrates: Not consistently. Sometimes gene modules are enriched in a specific type of gene, like metabolism genes, but other times, there is no clear pattern. Instead the gene modules often are mixtures of genes with many different functions. Just like the hidden nodes in a deep learning algorithm - sometimes they detect features that make sense to us, but other times they don't.

Moses: So that's why you call the black box "opaque."

Socrates: Exactly. The computational method is completely transparent, but in terms of understanding precisely what all the hidden nodes are looking for, it's not always clear cut. With everything linked to and affecting everything else, the logical flow linking the input to the output can be nearly impossible to penetrate. So the algorithms remain black boxes unable to explain the reasons behind their predictions, which also makes it harder for users to diagnose and repair problems.

Moses: I see.

Socrates: And there's another complicating aspect that is also very relevant to biology.

Moses: What's that?

Socrates: The final weights and biases of a trained network often depend on the random initial values that you start with. The gradient descent method takes you to the nearest valley of the cost function, but there can be more than one valley (Figure 11-5). So depending on where you start from, you can end up in a different valley. In other words, if you start with different random values for the weights and biases of the synapses, you can end up with different final values when the training is complete.

Moses: So a bunch of trained neural networks can be non-identical, but give similar error rates?

Socrates: Yes. And if the criterion for acceptable performance of the algorithm is less than 1% error, say, then they will all be good enough to solve the problem. Having multiple non-identical Good Enough Solutions, so-to-speak, can be actually useful for further improving the overall accuracy.

Moses: How so?

Socrates: Even though their overall error rates are similar, non-identical neural networks will tend to make different mistakes. For example, suppose that you've trained five neural networks to recognize handwritten digits. Say that one of them incorrectly predicts that a handwritten three is an eight, whereas the other four networks correctly predict the actual value of three. If you form a committee of the five networks and have them vote by majority rule, the committee will decide that the correct value is indeed three with 80% certainty. In practice, the error rate can fall to as low as 0.2-0.3% using a committee of networks to predict the hand-written digit values.

Moses: So the different non-identical networks act as cross-checks on each other?

Socrates: Exactly.

Moses: Do you really think that this is how our brains work? It seems to me that AI is very good at narrow tasks like recognizing handwritten digits, playing chess or even driving a car. But humans have to solve all kinds of general problems to survive in this world, not to mention new problems which they haven't encountered before. Take a toddler learning to walk, for example. It doesn't have a prepackaged training dataset to be trained on before it takes its first step.

Socrates: True, but remember, our neural network for identifying handwritten digits didn't work very well before it had been trained either – a 90% error rate. It had to cycle through successive forward and backward propagation steps in order to reach its optimal level of performance (Figure 11-6B). When you think about it, the toddler also goes through a similar iterative learning process, except that it's on-the-job training instead of pre-training. Each time the toddler attempts to walk is like a forward-backward propagation cycle. With each cycle, the error rate gradually declines. In machine learning, when you train an algorithm with a pre-defined training set, like we did with the handwritten digit algorithm, it's called *supervised learning*. When it's on-the-job training, like our toddler, it's called *reinforcement learning*. There's also a third category too, called *unsupervised learning*, where the goal is to discover patterns in unstructured data – like network science algorithms that cluster genes into co-expression modules. There are also deep learning algorithms that generate their own data so that they can train themselves.

Moses: That last sounds interesting - can you give me an example?

Socrates: There's a deep learning algorithm called Alpha-Go that was designed to play the Chinese board game Go [81]. Instead of being trained on games played previously by human players, Alpha-Go uses the rules of Go encoded into the algorithm to play games against itself. Since it doesn't require an external pre-packaged training dataset, it falls into the *unsupervised learning* category. By playing itself millions of times, it figures out the most successful moves to win the game. And it beats *supervised learning* algorithms which have been trained on games previously played by human players because it can play a virtually unlimited number of games against itself and explore strategies that humans have never even tried before. Now there's a new version called Alpha-Zero that's been generalized to learn other games like chess and Shogi by incorporating their rules into the algorithm so that it can self-train by playing against itself [82].

Moses: That seems promising.

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[81] **D. Silver** et al. Mastering the game of Go without human knowledge. *Nature*. 550:354-359, 2017.
[82] **D. Silver** et al. Mastering chess and shogi by self-play with a general reinforcement learning algorithm. arXiv:1712.01815v1 [cs.AI] 5 Dec 2017

Socrates: It is, although games like Go have discrete rules that can be easily programmed into an AI algorithm to allow self-training. It's less clear for other AI areas how to program algorithms to train themselves. Or for our own brains - the brain would have to imagine the rules beforehand, like the toddler imagining the best way to walk before actually trying it out.

Moses: I see what you're saying. To me, it sounds like *reinforcement learning* is the category most relevant to our toddler who's learning to walk. But there's one thing that I don't understand about the analogy between a deep learning algorithm and a toddler learning to walk.

Socrates: What's that?

Moses: Last time I checked, toddlers learning to walk don't know enough calculus to perform gradient descent calculations in the backward propagation step.

Socrates: Very good point, Moses, you don't miss a trick! Fortunately, there's an alternative to the gradient descent method.

Moses: That doesn't require a working knowledge of mathematics, right?

Socrates: Correct.

Moses: What is it?

Socrates: It's called genetic optimization.

Moses: That certainly sounds more biological.

Socrates: Indeed, it's exactly that - an evolutionary strategy modeled after biology. A fusing of deep learning with genetic optimization, directly inspired by Darwinian survival of the fittest [83]. It's called *neuroevolution*. You take a deep neural network and replace gradient descent in the backward propagation step with genetic optimization.

Moses: So how does it work?

Socrates: Instead of starting with a single neural network with randomly assigned weights and biases, and then repeatedly cycling it through forward and backward propagation steps using the gradient descent method, you start with a whole population of neural networks, each with different randomly assigned weight/bias combinations. Then you run them all through the forward propagation step, same as you would in a deep learning algorithm.

Moses: And then what?

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[83] From Gradient Descent vs. Neuroevolution: Towards Data Science - https://towardsdataScience.com/gradient-descent-vs-neuroevolution-f907dace010f; Neuroevolution: A different kind of deep learning - O'Reilly Media https://www.oreilly.com/ideas/neuroevolution-a-different-kind-of-deep-learning 18/23

Socrates: There are three stages – fitness evaluation, selection, and reproduction/ combination/mutation (Figure 11-7). You take the population of randomly-initialized neural networks, evaluate the fitness of each one, and select the fittest model for reproduction/combination/mutation to create variety in the next generation, and repeat over and over.

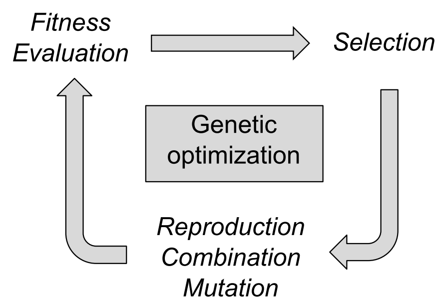

Figure 11-7. Schema of genetic optimization in neuroevolution deep learning algorithms.

Moses: How do you evaluate fitness?

Socrates: With a cost function.

Moses: Doesn't calculating a cost function require math? You promised me that our toddler wouldn't need to do any math.

Socrates: In the case of our toddler, the cost function is just how far it manages to walk before it falls down. No mathematics required, except for toddler to be able to perceive how close it gets to its goal.

Moses: I'll give you the benefit of the doubt. What comes next?

Socrates: Remember how we said that if you plot the cost function for different combinations of weights and biases in a neural network, it shows a curve with peaks and valleys (Figure 11-8). The peaks with high cost function values correspond to high error rates, and the valleys with low cost function values to low error rates. Since a random initial combination of weights and biases is not likely to put you at the bottom of a valley, the goal is to figure out how to alter the weights and biases to move to the bottom of the valley, where the error rate is lowest.

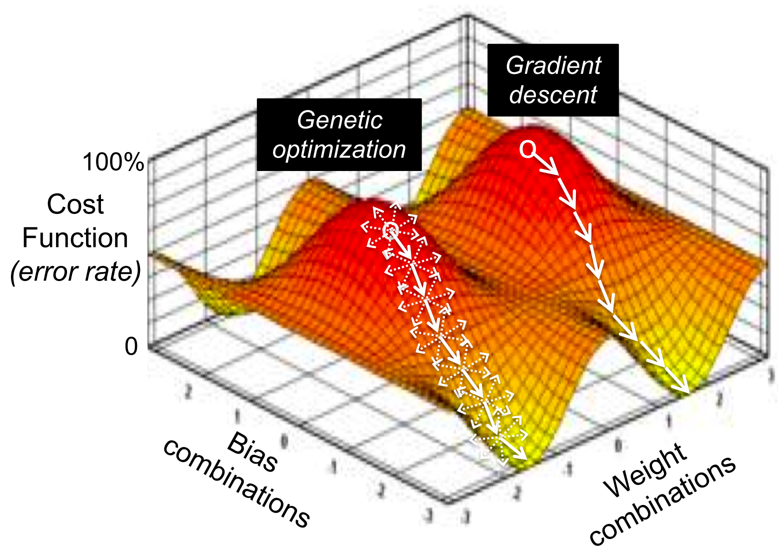

Figure 11-8. Gradient descent mathematically calculates how to alter the weightings to reduce the cost function and descend into the valley (right arrows). **Genetic optimization** randomly varies the weightings multiple times to locate empirically the direction that reduces the cost function to descend into the valley (left arrow clusters).

Moses: Yes, I remember. In conventional deep learning, that's what gradient descent does – it mathematically calculates how to adjust the weights and biases so that you descend downwards along the gradient, step-by-step, into the deepest nearest valley (Figure 11-8, arrows).

Socrates: In genetic optimization, you don't need to know the exact mathematical form of the cost function like you do for the gradient descent method. Instead, you take a population of models with randomly selected different weight/bias combinations and run them all through the forward propagation step. Next you evaluate the cost function for each model, which is the fitness evaluation step. Then you select the one that has managed to walk the furthest, i.e. the fittest model with the lowest cost function. That's the selection step. Next in the the reproduction/combination/mutation step, you make small random alterations to the weights and biases to create the next generation of models. Then you repeat the process, over and over again. With each iteration you pick the model that lowers the cost function the most – in other words, in the direction of the valley where the optimal solution lies (Figure 11-8, arrow clusters). When the reproduction/ combination/mutation step fails to lower the cost function any further, then you are at the bottom of a valley and the cost function is optimized. It's not as efficient as computing the most direct route into the valley mathematically using gradient descent, because you have to explore a multitude of directions in each generation, and they may not identify the most direct route to the valley. But it works nevertheless, even when you don't have any detailed pre-knowledge of the shape of the curve relating the cost function to the weights and biases.

Moses: So it's not completely random, like when we randomly guessed at the weights and biases to see whether we could chance upon a combination that had a very low cost function. That was like looking for a single atom in the universe and got us nowhere (Figure 11-6A). This is really more of a directed random search, based on survival and selection of the fittest randomly-modified neural network model.

Socrates: Exactly. The small random perturbations to the weights and biases of the best-performing neural networks are effectively exploring the cost function surface to locate the direction that reduces the cost function's value the most (Figure 11-8, arrow clusters). By trial and error, it follows the local gradient to optimize the cost function at its low point in the valley. The beauty is that it does it without having to perform explicit mathematical calculations like in the gradient descent method.

Moses: Very clever. What kind of problems has it worked well for?

Socrates: Funny you should ask.

Moses: Why's that?

Socrates: Because we've been talking about toddlers learning to walk.

Moses: That's where the neuroevolution approach has been successful?

Socrates: Toddlers, no - they learn just fine by themselves. But robots learning to walk are a different story – for them, neuroevolution deep learning algorithms have been very effective. What's more, some very intriguing findings have come out of it.

Moses: Such as?

Socrates: For one, it turns out that fitness is not the only useful criterion for selecting the best algorithms in each new generation – selecting for novelty can also be quite valuable.

Moses: How so?

Socrates: As Ken[84] has explained it, suppose that your algorithm generates a population in which some robots lurch forward and are able walk a short distance, whereas other robots exhibit an oscillating motion, but immediately fall over. If the fitness criterion is walking distance, the lurchers would be selected and the oscillators dropped. But what if the best walking ability is achieved by combining lurching and oscillating? Then selecting the lurchers and dropping the oscillators based on fitness might ultimately be a dead end. If instead of dropping the oscillators, you choose to reproduce/combine/mutate them with lurchers, the combination has the potential to evolve into a vastly improved and much more natural walking ability. In other words, the road to the best result can be deceptive, especially when the whole is greater than the sum of the parts, as in this case.

Moses: So you're saying that selecting for fitness and novelty can be more effective than selecting for fitness alone.

Socrates: Yes, that's exactly what I'm saying. And more than that, there's also an obvious danger in selecting only the most fit for reproduction/combination/mutation: if selection is too narrow, it drains diversity from the population.

Moses: Then the goal should not be to find a single optimal solution, but a broad class of solutions for the task at hand.

Socrates: That's exactly what happened with the robots. A robot walking algorithm called MAP Elites [85] used a selection strategy combining both fitness and novelty to uncover a large collection of alternative robot gaits, some more effective than others. If one gait mechanism failed as a result of damage to the robot, like a broken leg, the robot could rapidly call into action an alternative mechanism to continue to walk (Figure 11-9). Just like an animal whose leg is injured in an accident, but learns quickly how to compensate and limp away.

Moses: That's fine for an artificial neuroevolution deep learning algorithm, which you can select for whatever you want by modifying the program, whether it increases fitness or not. But in biological evolution, natural selection is based on survival of the fittest, not survival of the most novel.

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[84] **Kenneth O. Stanley**, Neuroevolution: A different kind of deep learning - O'Reilly Media https://www.oreilly.com/ideas/neuroevolution-a-different-kind-of-deep-learning 18/23

[85] **A. Cully, J. Clune, D. Tarapore, J.B. Mouret**. Robots that can adapt like animals. *Nature*. 521:503-7, 2017.

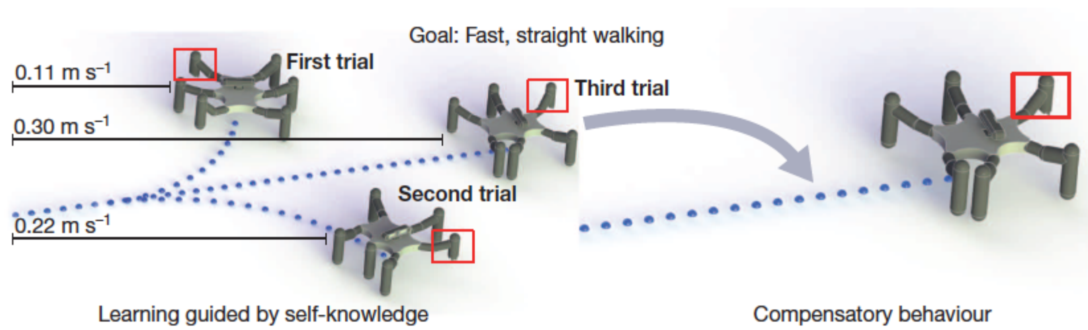

Figure 11-9. MAP Elites neuroevolution algorithm for training robots to walk. When one of the robots legs (red box) was damaged so that the robot could no longer walk in a straight line (First trial), the algorithm tried two alternative walking method, one that failed to compensate (Second trial) but another that successfully compensated (Third trial). From reference in footnote 84.

Socrates: That depends how you define fittest. In the case of the robot, if you define fitness by how far and fast the robot can walk on a smooth surface, survival of the fittest will select for the fastest walker who doesn't fall on a smooth surface. The problem is that if the environment changes and the surface becomes bumpy, then another walking mechanism may perform better. Like we said before (Figure 9-1), traditional top-down engineering design emphasizes efficiency over robustness and adaptability. But bottom-up biological engineering prizes robustness and adaptability over efficiency, since if a living organism fails, there is no engineer to reprogram it like there is for a computer algorithm. Diversity is key in biology. That's why living systems build in so much redundancy. If the goal is to perform a task that never changes, the best solution is the most efficient solution. But if the goal is to survive when the goal posts are continually moving, a diverse population of Good Enough Solutions, even if they not all as good as the best solution, is much more reliable overall.

Moses: Very neat. I guess that's a major advantage of the neuroevolution approach over conventional deep learning. Deep learning is serial – it takes one algorithm and improves it on each forward-backward propagation cycle. At the end, you have a single algorithm that's been optimized to solve a problem. But with neuroevolution, it's more like parallel processing - you can end up with a whole population of algorithms that all work fairly well, with the flexibility of selecting the one that works best for the conditions at hand. Since what works best for one set of conditions may not be the best for another set of conditions, the algorithm can adapt.

Socrates: I couldn't have said it better myself, Moses! And there's another bonus to neuroevolution over conventional deep learning.

Moses: What's that?

Socrates: In conventional deep learning, you begin with a single deep neural network that has a specific pre-defined architecture - so many hidden layers containing so many hidden neurons. Then you use forward and backward propagation with gradient descent to optimize the weights and biases. In the neuroevolution approach, however, you don't have to stop there. Not only can you use genetic optimization to find the best weights and biases, you can also use it to evolve the best network architecture – for example, to alter the number of neurons in a hidden layer or add additional hidden layers to see how the fitness is affected. Neuroevolution has much more plasticity than conventional deep learning for that reason.

Moses: That does seem to be very relevant to biology. For example, during development the architecture of the brain changes dramatically, with neurons forming new synapses all the time.

Socrates: That plasticity is a major advantage of neuroevolution – with genetic optimization, the network architecture can evolve in an open-ended way.

Moses: Very impressive. But there's still one other issue that puzzles me about the deep learning algorithms as a model for how our brain's work.

Socrates: What's that?

Moses: In the deep learning algorithms that we've discussed so far, the synapses go only in one direction, from the input layer through the hidden layers to the output layer. In our brains, synapses don't just go in one direction – they can connect within and between layers in either direction. That creates many more potential feedback loops within and between the hidden layers. Don't our brains depend on that, to generate all those emergent dynamical elements like attractors, repellers, switches, excitable elements and oscillators? Dynamics are going on all the time in our brains, even when we're asleep and not consciously thinking.

Socrates: Very good point, Moses. You are right that we've discussed only feed-forward neural networks so far, where synapses connect neurons only in the forward direction from deeper to shallower layers. The only real feedback in conventional deep learning like CNNs is in the optimization of the cost function by the forward-backward propagation cycle.

Moses: But couldn't a deep learning algorithm also incorporate bidirectional synapses between the neurons in the hidden layers?

Socrates: Of course.

Moses: And?

Socrates: Neural networks with feedback as well as feed-forward between the hidden layers are called Recurrent Neural Networks (RNNs). They've been very useful, particularly when the input is a stream of data over time, such as speech recognition and grammar learning, handwriting recognition, music composition and rhythm learning, and even simulated walking and running. In those cases, the correct identification of the object of interest, like a spoken word, is improved by knowing what comes immediately before or after it. So they are designed to incorporate feedback loops and time delays between the neurons in the various layers.

Moses: Do they generate dynamical elements like attractors, repellers, switches and oscillators?

Socrates: Most definitely. In fact, they are trickier to train because adjusting the weight and biases can trigger all sorts of spontaneous dynamics, such as run-away excitation or chaos. It's like the algorithm starts having a seizure - the cost function suddenly takes on a very high value. Under those conditions, it's very difficult to judge how to change the weights and biases to move you off the hill and towards a valley on the cost function surface (Figure 11-8). That's one reason why AI researchers generally prefer feed-forward networks, which aren't as prone to those complex and exotic behaviors. Right now, RNN's are better suited for applications that need to discriminate input patterns, like speech recognition, rather than those that need to generate complex output patterns [86].

Moses: But if those issues can be tamed, then there's no reason that the hidden layers in RNNs can't generate essential dynamical elements like attractors, repellers, switches, oscillators and even spontaneous pattern formation that our brains depend on, right?

Socrates: Indeed. In fact, progress has already been made incorporating dynamical behaviors into AI. For example, there's an RNN algorithm in which the neural network consists of neuronal oscillators, which have been coordinated and trained to simulate a

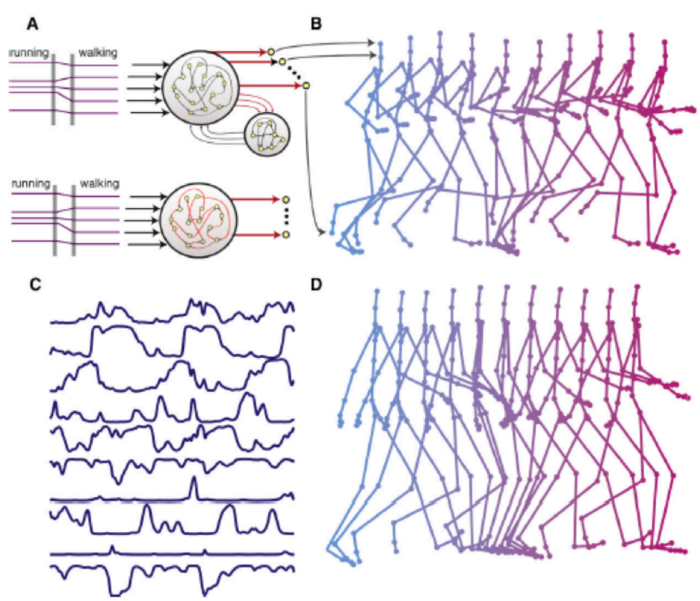

Figure 11-10. A RNN (**A**) in which feedback and time delays generate oscillating neural units (**C**) that have been trained to simulate a human running (**B**) and walking (**D**). Reproduced from D. Sussillo, L.F. Abbott *Neuron*. 63:544-57, 2009.

[86] **D.V. Buonomano**. Harnessing chaos in recurrent neural networks. *Neuron*. 63:423-5, 2009.
D. Sussillo and L.F. Abbott. Generating coherent patterns of activity from chaotic neural networks. *Neuron*. 63:544-57, 2009.

human walking or running (Figure 11-10).

Moses: Just like our toddler.

Socrates: Exactly. All sorts of emergent properties become possible with feedback and time delays in RNNs.

Moses: Where do you suppose this is all heading? Is AI going to surpass human intelligence?

Socrates: For performing many specific tasks, like playing games or interpreting x-rays, it already has. But it's still only weak AI, also called artificial narrow intelligence or ANI for short, which is based almost entirely on making statistical associations to identify patterns. Current algorithms have no understanding of cause-effect connections. The breakthrough will be strong AI, in which the algorithm can perform any task as well or better than a human being. And it's hard to imagine that can be accomplished without explicitly incorporating causal reasoning tools into the algorithm, which is currently being actively explored. As Judea has put it [87]:

> "This hallmark of human cognition is, in my view, a necessary (though not sufficient) ingredient for achieving human-level intelligence. This ingredient should allow computer systems to choreograph a parsimonious and modular representation of their environment, interrogate that representation, distort it through acts of imagination, and finally answer "What if?" kinds of questions."

Personally, if I were a betting sea lion, I'd put my money on a causal reasoning-enhanced neuroevolution algorithm incorporating a deep learning RNN with genetic optimization.

Moses: Why?

Socrates: Do you really have to ask at this point?

Moses: You mean because of feedback?

Socrates: Of course - that's the key to all self-organizing phenomena in life! Especially intelligence. If you define intelligence as the ability to learn how to solve a problem, how else can you possibly learn anything without some form of feedback to tell how far or close you are to achieving your goal? It's the same for training an AI algorithm or the human mind. In fact, it applies broadly to anything that learns, including the evolution of life itself!

[87] **Judea Pearl.** The seven tools of causal inference, with reflections on machine learning. *Communications of the ACM* **62**(3): 54-60, 2019.

Chapter 12: Genomic Learning

Moses: What do you mean, feedback is the key to the evolution of life itself?

Socrates: Life doesn't just get to survive. She has to learn to survive by adapting to whatever unanticipated environmental and ecological changes nature throws at her. And like we just said, learning requires feedback to assess changes and respond accordingly. Just like a living organism has to learn to survive during its lifetime by sensing its environment to avoid predators and locate food, each genome has to learn to survive from generation to generation by adapting to ecological changes to keep the species well-suited to its environment.

Moses: You make it sound like the genomes are making conscious intelligent choices.

Socrates: If we define intelligence as the ability to solve problems, then what does consciousness have to do with it? Haven't you labeled your AI algorithms as intelligent, even though they're not conscious, at least so far? Perhaps you should think of the learning process in biological evolution in the same way.

Moses: You mean with the input layer as genes and the output layer as phenotypes?

Socrates: Exactly, and all of the scale-free biological networks that we've been talking about as the hidden layers that are ultimately responsible for converting the genotype into the phenotype – genes organized into gene co-expression networks, linked to protein-protein interaction networks, linked to metabolite networks, organellar networks, cellular networks, tissue and organ networks and so forth, until the system finally spits out the phenotype (Figure 12-1)!

Moses: They would certainly qualify as a black box in which everything affects everything else!

Socrates: Only with nodes and links (edges) instead of neurons and synapses like a deep learning neural network.

Moses: However, unless you believe in reincarnation, an individual genotype goes through life only once, so it doesn't have the opportunity to try to learn to perform better on a second round. That's different from a deep learning network that cycles repeatedly between forward and backward propagation steps during the training or reinforcement period, in order to improve accuracy on each go-around.

Socrates: True, but unlike an individual genotype, the genome of a species doesn't perish after one cycle – it continues on for as long as successful individuals continue to reproduce. Take yourselves, for example. Humans have around 20,000 or so genes. Each gene has many variants reflecting differences in DNA sequences – like single nucleotide polymorphisms (SNPs) arising from random mutations accumulated over the generations. Those mutations can have anywhere from trivial to major effects on a gene's function, with the result that each individual's genotype is a combination of different gene variants producing a unique phenotype. That's why some people are tall and others are short, for example.

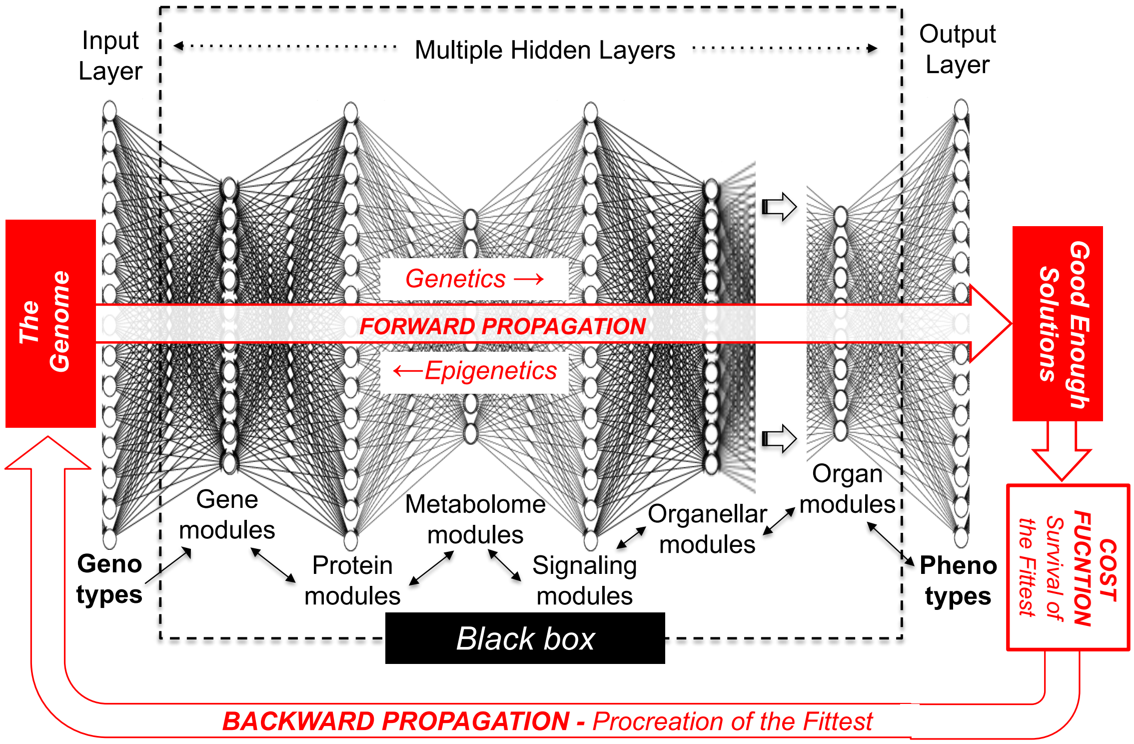

Figure 12-1. Genomic learning as a deep learning algorithm (compare to Figure 11-4)**.** Genotypes (the input layer) are processed through multiple bidirectionally-linked biological networks (black box of hidden layers) to create phenotypes (the output layer), constituting the forward propagation step (genetics + epigenetics). The diverse phenotypes represent a population of Good Enough Solutions that compete to survive (the cost function) and procreate in order to have their genotypes preserved in the next generation, constituting the backward propagation step utilizing genetic optimization.

Moses: Ah….now I see where you're heading! Instead of an individual genotype, you're saying that the entire genome is the input layer. Each genotype is just a different combination of gene variants, like a different set of weights and biases in a neural network, instructing the hidden biological network layers how to generate a unique phenotype.

Socrates: Perhaps we should call it *genomic learning*, to distinguish it from the other type of biological learning that our brains perform to help us survive during our individual lifetime.

Moses: The idea of genomic learning as an algorithm makes sense, I suppose. But it would have to contain a lot of feedback loops in the hidden layers, like an RNN. It couldn't be a purely feed-forward neural network like most deep learning algorithms.

Socrates: Very good, Moses, I agree. An individual's phenotype isn't determined just by its genotype. It's also determined by *epigenetics* - how the hidden biological network layers inside the black box respond to the environment and then feed back to regulate genes in the input layers. Epigenetics is what causes one cell to adapt to clues in its local environment and become a liver cell, whereas another differentiates into a heart cell, despite each containing the identical set of gene variants as every other cell in the body.

Moses: Makes sense. Otherwise, if the genotype completely specified the phenotype, without any epigenetic influences feeding back in the other direction, then we'd just be a large blob of the same type of cell, without any organs.

Socrates: Not only that, but those epigenetic feedback loops within and between the hidden biological networks are also essential for generating emergent phenomena like biological clocks and switches to turn off and on various pathways that your organs depend on. Those are the fundamental dynamical building block essential for life's many functions, like cell division, the heartbeat, neural signaling, just to mention a few.

Moses: Then we have all we need for the forward propagation step in our genomic learning algorithm. Genetically-encoded information flows from the input layer through the various hidden layers of networks to the output layer, and epigenetic feedback flows in the opposite direction, like the bi-directional links in an RNN (Figure 12-1).

Socrates: And how about the backward propagation step? What do you think is most appropriate, gradient descent or genetic optimization?

Moses: I don't know about your genome, but mine is in the same predicament as the toddler learning to walk – it doesn't know how to add or subtract, much less perform mathematical calculations to compute gradients. That pretty much excludes gradient descent. So it has to be genetic optimization.

Socrates: I agree. And remember, genetic optimization was inspired by biological evolution and natural selection in the first place! So far so good. Now all you have to do is to identify the cost function and the three components of genetic optimization - fitness evaluation, selection and combination/reproduction/mutation (Figure 11-7).

Moses: The fitness evaluation step is where the cost function comes into play. How about using survival as the cost function? Well-equipped to survive is low cost/high fitness and poorly-equipped to survive is high cost/low fitness.

Socrates: I can live with that. How about the selection step?

Moses: Survival of the fittest? The genotypes that produce the fittest phenotypes are ones that survive and contribute their gene variants to the next generation.

Socrates: Very good. And last, but not least, the combination/reproduction/mutation step? Where do all the gene variants that make up the different genotypes for each new generation come from?

Moses: Random mutations?

Socrates: Ultimately that's how the different gene variants originate. But random mutations occur relatively slowly. It's not like a machine learning algorithm in which you can set the mutation rate to whatever you want by just typing a new number into the program. You need something faster, that reshuffles the gene variants with each new generation.

Moses: Sex?

Socrates: Perfect. Once you've accumulated enough random mutations to create a large pool of gene variants, sexual reproduction is a very efficient method to shuffle them around for each new generation, rather than waiting for *de novo* mutations to occur. Even primitive lifeforms that reproduce asexually, like bacteria, have developed other ways to transfer genetic material laterally between individuals rather than depend exclusively on random mutations [88].

Moses: That's it then - survival and procreation of the fittest are the equivalents of genetic optimization and backward propagation (Figure 12-1)! Only phenotypes that survive long enough to procreate have their gene variants incorporated into the next generation. And that completes the genomic learning feedback loop.

Socrates: And without requiring that the genome have any formal math skills! Nature just bets that if both parents have been successful at surviving long enough to procreate, combining them in their offspring has a statistically better chance of being equally or even more successful.

Moses: Is that a reliable assumption, though? Can you really assume that if two genotypes are successful, mixing their gene variants together will be equally or more successful? Seems like linear thinking applied to a very nonlinear situation.

Socrates: Very good, Moses! If the black box is very nonlinear and produces a whole that is greater than the sum of the parts, there's no guarantee that combining the two successful halves from the parents won't produce a disaster in the offspring. If that happened, the algorithm would suddenly grind to a halt.

Moses: How does nature solve that problem?

Socrates: By not putting all of its eggs in one basket, literally speaking.

Moses: What do you mean?

Socrates: It's not just a single fittest male who gets to mate with a single fittest female. It's a whole population of the most fit males and the most fit females who get to mate. The odds of all of those mating couples producing defective offspring are pretty small. Some may be less successful than their parents, but some will be more successful.

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[88] All prokaryotes like bacteria reproduce asexually without the formation and fusion of gametes, but have also developed mechanisms for lateral gene transfer such as transformation and transduction that facilitate genetic recombination in meiosis. Asexual reproduction has short term benefits when rapid population growth is important or in stable environments, but lateral gene transfer mechanisms allow more rapid generation of genetic diversity when adapting to changing environments.

Moses: Sort of like a committee of deep learning algorithms, where there can be multiple Good Enough Solutions that meet adequate criteria to survive.

Socrates: Indeed. That explains why genetic diversity is so critical. As long as some members of the new generation are good enough to survive and procreate, the cycle of life continues and the genome learns to adapt! Not only that, with sex, only gene variants that have already proven to be successful in their parents get incorporated into the next generation. That's less risky than relying completely on random mutations for each new generation, since random mutations are just as likely to be deleterious as beneficial.

Moses: Nature never misses a trick, it seems. Amazing, isn't it, how our genomes have learned to survive and evolve by using feedback in such an empirical way?

Socrates: There's no other choice, really. Remember how hopeless pure trial-and-error was in trying to guess at a combination of the weights and biases that performed well? Even for a shallow neural network with only a single hidden layer, like the handwritten digit recognition algorithm, random trial-and-error searching got us nowhere fast (Figure 11-6A).

Moses: But when the trial-and-error random search was directed by genetic optimization, it was a completely different ball game. Like that deep learning neuroevolution algorithm MAP Elites [89] that trained robots to walk (Figure 11-9). The algorithm could generate many Good Enough Solutions in a reasonable amount of time. Some that worked better under some conditions, and others that worked better under others.

Socrates: If the goal is to perform a task that never changes, the most efficient solution is often the best solution. But for living things, the environment is always changing, so that what's best today may be obsolete tomorrow. If the goal is to survive when the goal posts are continually moving, a diverse population of Good Enough Solutions is much more reliable than a single best solution.

Moses: Very succinct, I like the way that you put that.

Socrates: What?

Moses: When you said "If the goal is to survive when the goal posts are continually moving, a diverse population of Good Enough Solutions is much more reliable than a single best solution."

Socrates: Indeed, and it's more than just a platitude! It's the key to resolving one of the most long-standing paradoxes in evolutionary biology.

[89] **A. Cully, J. Clune, D. Tarapore, J.B. Mouret**. Robots that can adapt like animals. *Nature*. 521:503-7, 2017.

Chapter 13: Good Enough Solutions

Moses: One of the most long-standing paradoxes in evolutionary biology?

Socrates: The *Robustness versus Adaptability Paradox*.

Moses: What's that?

Socrates: Has it ever occurred to you how a species can be simultaneously robust and adaptable?

Moses: What do you mean?

Socrates: Living organisms have to be robust enough to survive in a fluctuating environment. That is, they have to maintain a stable phenotype as the environment changes. But to evolve, living organisms also have to adapt their phenotype as the environment changes. So how can living organisms both resist and embrace changes to their phenotype at the same time? It would seem that robustness and adaptability are incompatible with each other.

Moses: I see what you mean. That's a really good question. Has it been resolved?

Socrates: Eve[90] came up with a pretty clever solution.

Moses: Who is Eve?

Socrates: She's a neuroscientist who has studied lobsters for most of her career - their somatogastric ganglion to be specific.

Moses: Their somato-what?

Socrates: It's a neural circuit consisting of about 30 neurons in a lobster's digestive tract that controls its pyloric sphincter. That's the muscle that regulates the passage of food between the stomach and the intestines (Figure 13-1A&B). The neurons in the ganglion generate a bursting pattern that causes the pyloric sphincter to open and close to transfer partly digested food from the stomach into the intestines.

Moses: So how is this ganglion related to the *Robustness versus Adaptability Paradox*?

Socrates: Eve observed that the ganglia from different lobsters showed very similar bursting patterns. But what surprised her was that different animals used completely different combinations of ion channel proteins controlling electrical activity to create the similar bursting patterns (Figure 13-1C).

Moses: So what?

Socrates: Well, you might have expected that through natural selection, lobsters would have evolved towards the most ideal combination of ion channels to generate the most

[90] **Eve Marder, PhD** (b. 1948), the Beinfield Professor of Neuroscience at Brandeis University, is known for her pioneering work on small neuronal networks which her team has interrogated via a combination of complementary experimental and theoretical techniques.

efficient and reliable bursting behavior. You know, in the spirit of “the most efficient solution is the best solution.” But instead, lobsters evolved many different combinations that all seemed to perform about equally well as far as the lobsters were concerned. She called them Good Enough Solutions.

Moses: Why Good Enough Solutions?

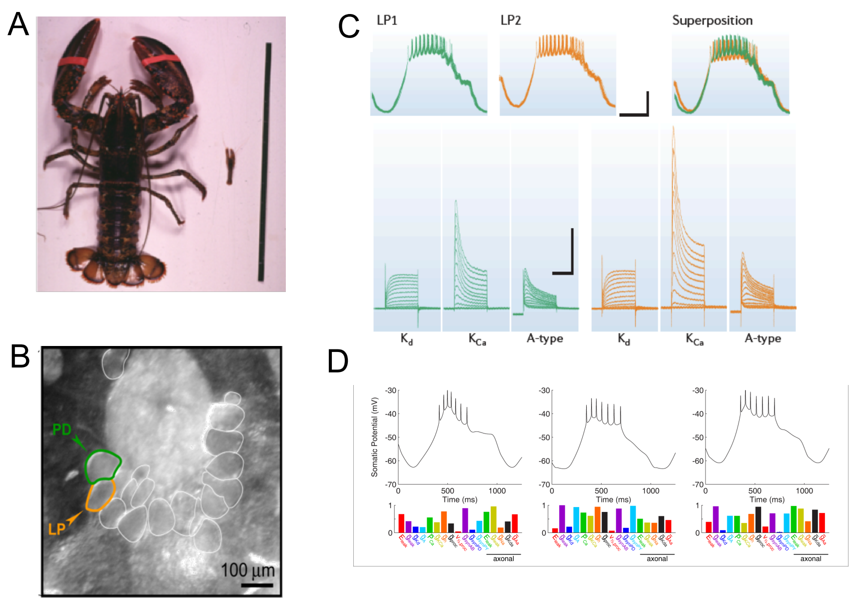

Figure 13-1. A. Lobster. **B.** Lobster’s somatogastric ganglion. **C.** Neuronal bursting patterns (above) and ion channel conductances (below) recorded from 2 different lobster ganglia (green & orange traces, respectively). **D.** Computer simulations of similar bursting patterns using different combinations of ion channel conductances, each a unique “Good Enough Solution.” Reprinted from E. Marder and J.M. Goaillard. Variability, compensation and homeostasis in neuron and network function. *Nat Rev Neurosci*. 7:563-74, 2006.

Socrates: Because, just like us, lobsters don’t need the best possible solution in order to survive. They just need a Good Enough Solution, which in this case means good enough keep the food moving through their digestive tracts. It doesn’t really matter whether the bursts emanating from the ganglion have exactly the same duration or frequency from lobster to lobster, as long as they occur within an acceptable range. Just like your resting heart rate doesn’t have to be exact – anywhere between 60-100 beats per minute is considered normal.

Moses: But how can two lobsters use completely different combinations of ion channels and still get very similar bursting patterns from their ganglia?

Socrates: Think of a ganglion as a system of inputs and outputs, like a machine learning neural network AI algorithm. The lobster’s somatogastric ganglion has many adjustable inputs, namely all those various types of ion channels. But the output is simpler and has fewer constraints - namely, an acceptable bursting pattern. When a system has a large number of adjustable input parameters but smaller number of constraints on the output, then there are often many combinations that will work just as well. For example, a predator has to be faster than its prey to catch it, but it doesn’t really matter whether it's a little bit faster or a lot faster – either is good enough to get the job done. Or take height and weight variation among humans – to function normally in society, it doesn't really matter whether you're on the tall side or on the short side, or slender or heavy. As long as you fall within a reasonable range, you are good enough to functional normally.

Moses: Interesting theory. How did Eve prove it?

Socrates: She incorporated the various ion channel conductances into a mathematical model of the neurons in the ganglion, and adjusted their input values to reproduce a typical bursting pattern as the output. Then she experimented by randomly altering different ion channel conductances, around 600,000 times in all, and recorded how the bursting pattern was affected in each case. Most of the time, the bursting was disrupted, but in about 1,500 of the mutated models, the bursting pattern remained reasonably similar to that in the original model (Figure 13-1D).

Moses: So those 1,500 mutated models were all Good Enough Solutions to accomplish the task at hand?

Socrates: Exactly.

Moses: But why would nature work that way? What's the advantage?

Socrates: That's where Eve had her key insight into the *Robustness versus Adaptability Paradox*.

Moses: Which was what exactly?

Socrates: Say that you and I are two lobsters swimming around in a bay. The bay has plentiful sea life to feed us, so that our somatogastric ganglia are bursting away, moving digested food through our stomachs as we scavenge along the ocean floor. But since our genetic makeups are different, the neurons in your ganglion and my ganglion use different Good Enough Solutions to regulate the bursting. Now suppose that my bursting has a high dependence on a particular type of potassium channel, say calcium-activated potassium channels, whereas yours relies on a different type of potassium channel. Both yield perfectly Good Enough Solutions to produce an acceptable bursting activity as we roam the bottom in search of our next meal. What does that tell you?

Moses: It tells me that we are both robust enough to digest our scavenged food normally despite the ambient seasonal environmental changes that we encounter.

Socrates: Correct. But now imagine that some business builds a factory along the shore of our bay and begins dumping waste into the water. And one those waste products happens to block calcium-activated potassium channels. What happens now?

Moses: Ah, now I see where you're heading. The neurons in your somatogastric ganglion depend on those channels to maintain normal bursting activity, so you are in trouble. Without being able to digest any food, you could be done for. But not me. I will be fine, since I don't depend on calcium-activated potassium channels for my bursting activity. The lobsters like you will perish, but lobsters like me will survive to repopulate the bay.

Socrates: Exactly.

Moses: What you're saying is that both of us function well enough to survive when the environment is fluctuating normally. But when an unanticipated change occurs, such as dumping a chemical waste into the bay, some of us will be more susceptible than others because our genetic makeups are different and have resulted in different Good Enough Solutions!

Socrates: Exactly. And that, in a nutshell, was Eve's big insight into the *Robustness versus Adaptability Paradox* – from an evolutionary standpoint, *robustness* operates at the level of individuals, whereas *adaptability* operates at the level of the population. Those two seemingly contradictory properties can be compatible because they are acting at different scales. They are complementary interacting opposites – Yin and Yang.

Moses: How do you know it applies to more than just to lobsters?

Socrates: Because there a lot of equally compelling examples.

Moses: Like what?

Socrates: Mice, for instance. Do you know how they became such a popular choice for modern genetic studies?

Moses: Not really.

Socrates: They have quite an interesting history. Your ancestors first began breeding mice as pets in China around 1100 BCE. By the seventeenth century, pet Japanese mice were introduced into Europe, and by the nineteenth century, inbred mice had become something of a rage, especially in Victorian England. The mouse enthusiasts even formed their own organization, The National Mouse Club, which held its first competition in 1895 to judge best color, body shape, behavior and other features. They called them "fancy mice." As it turns out, because so many inbred strains were already available and they breed so readily, with a new generation every month or so, that's how those so-called fancy mice ended up becoming a mainstay for genetic studies in modern mammalian biology. From a genetic standpoint, mice also span quite a wide range – in fact, if you try to mate the strains that are genetically the least related, the pups aren't even viable and don't survive.

Moses: What does that have to do with the *Robustness versus Adaptability Paradox*?

Socrates: Because each of those the inbred mouse strains represent a different Good Enough Solution for the mouse genome.

Moses: How do you know that?

Socrates: Jake[91] and his colleagues at UCLA discovered it. They collected over a hundred different inbred mouse strains, all normal mice living normal lives with normal life spans under normal domesticated conditions. Mice from the same inbred strain are genetically identical, so that when they express their genes, the levels, measured with DNA microarray chips, are very similar from one mouse to the next - no surprise there. But when Jake and his colleagues compared gene expression levels in mice from different inbred strains, the patterns were completely different (Figure 13-2)!

Moses: So what?

Socrates: One might have expected that natural selection would have converged towards a single ideal gene expression pattern for the ideal domesticated mouse adapted to living in a cage. But instead, different strains had evolved very different patterns, just like lobsters. Except with mice, the different gene expressions patterns could only be due to genetic differences, rather than to subtle differences in the environment. That's because the gene expression differences occurred only between strains, but not within strains.

Moses: But how do you know whether the different gene expression patterns have any significance? Maybe they are inconsequential and have no effect on the phenotype.

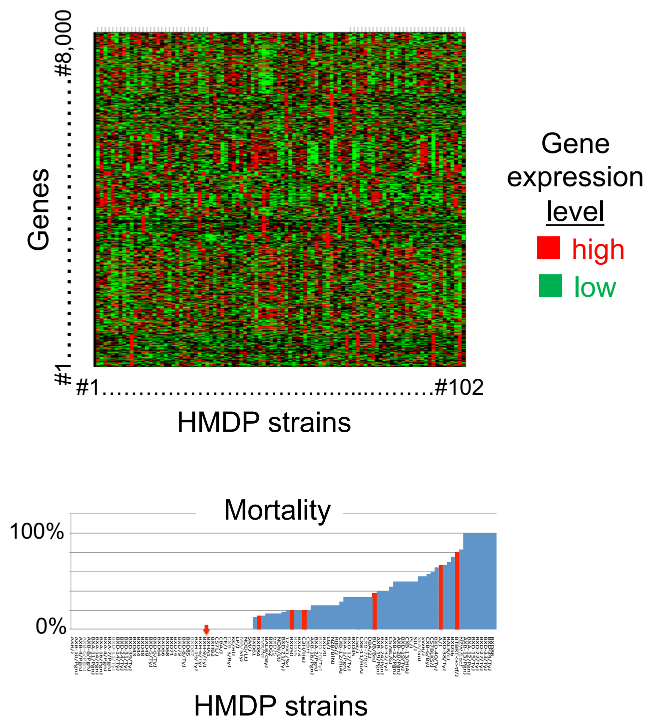

Figure 13-2. Gene expression patterns (above) and mortality from cardiac stress (below) in 102 different strains of inbred mice (HMDP), showing that different cardiac gene expression patterns confer differential susceptibility to cardiac death. Courtesy of Jake Lusis and Yibin Wang.

Socrates: Because that's not what Jake and his colleagues found. When they exposed different mouse strains to a stressful environment, different strains responded differently. On a high fat diet, mice from some strains became obese while others maintained a normal weight. Some strains developed atherosclerosis but others didn't. If their hearts were stressed, some

[91] **A. Jake Lusis, PhD**, Distinguished Professor of Medicine, Human Genetics, Microbiology, Immunology & Molecular Genetics at the David Geffen School of Medicine at UCLA in Los Angeles, CA.

strains developed heart failure and died suddenly, while others remained fine (Figure 13-2). And so forth.

Moses: Did the response to the new stress correlate with the gene expression pattern?

Socrates: Correct again. Indeed, that was why Jake and his colleagues developed the mouse panel in the first place. Their goal was to analyze how gene expression patterns correlated with susceptibility or resistance to weight gain, atherosclerosis, heart failure and other conditions, so that they could identify the important genes and uncover the molecular pathways involved.

Moses: Very clever! And it does seem to support the Good Enough Solutions idea, since all the strains were perfectly robust under normal environmental conditions.

Socrates: Indeed. With about 20,000 genes and multiple variants of each gene to combine in different ways, it's hardly surprising that many different combinations can produce a Good Enough Solution for a healthy domesticated mouse living in a cage.

Moses: But if the environment changes due to some new type of stress, some of those Good Enough Solutions can't adapt effectively and perish, whereas others are able to adapt and survive. Pretty neat. That would protect the mouse genome from extinction when some major environmental calamity occurs. What are some other examples?

Socrates: Take bacteria, for instance – one of the rare instances of biological evolution that you can observe in real time right before your eyes. Suppose that you culture strains of *E. Coli* in a Petri dish. All of the strains are Good Enough Solutions to survive and thrive under normal culture conditions. But now suppose that you add an antibiotic to the dish. Most of the bacteria will die, but some strains may have gene variants that confer resistant to the antibiotic. They survive and multiply. After a few days, the drug resistant strains have completely taken over the rest of the culture.

Or take cancer. Most cancers contain a genetically heterogeneous population of malignant cells, all of which have proven themselves to be Good Enough Solutions for avoiding the body's natural defenses. When you treat the cancer with a chemotherapeutic regimen, most cancer cells die, hopefully enough to cause a remission. However, if some cancer cells have a different genetic composition that confers resistance to the chemotherapy, they can survive and eventually repopulate the tumor. When the patient has a recurrence, the same drugs often don't work the second time around.

Moses: I guess that could also explain why some people get side effects to a drug, but others don't.

Socrates: Indeed, another excellent example. There are a whole group of commonly-used drugs that were originally thought to be safe, but later were discovered to pose a significant risk of causing sudden death due to cardiac arrhythmias. It turns out that they all block a specific type of cardiac potassium channel called HERG that helps to repolarize and relax your heart after each heartbeat. Since the heart has many different types of potassium channels, individuals with different genetic makeups can use different combinations to repolarize their heart cells. They all are Good Enough Solutions to repolarize and relax the heart under normal conditions, but the ones that rely heavily on HERG channels have a high risk of life-threatening arrhythmias when they take one of those HERG-blocking drugs. Everyone else is fine.

Moses: I bet I can think of few more examples, now that you mention it. Like some people get cancer, lung or heart disease from smoking tobacco, whereas others live to a hundred smoking two packs a day. Same for bad diet and lack of exercise – some die young from a heart attack, whereas others live a long life. They could all be different Good Enough Solutions in a population that shows differential susceptibility to an unhealthy environmental stress.

Socrates: That's why genetic diversity is so important. Your genome has learned that it's literally dangerous to put all of its eggs in one basket. For a species to survive, its genome has to be prepared to deal with unexpected challenges. For most of human history, people who are naturally obese on an unrestricted diet had a survival advantage because they were better equipped to survive near-starvation conditions during famines. In other words, for hundreds of thousands of years, genes promoting obesity were selected for over genes promoting leanness. But now that food has become plentiful in developed countries, there is an epidemic of obesity that is shortening the life span of an increasingly large fraction of the population. So the tables have turned and now the naturally lean people have the survival advantage!

Moses: Perhaps if we can find the genes that cause obesity and other common diseases, we can cure them by replacing them with normal genes. Then those naturally obese people wouldn't have to die prematurely.

Socrates: A wonderful concept in principle! That was the dream when the Human Genome Project was completed in 2001. As David [92] put it:

> "Individual humans differ from one another by about one base pair per thousand. These 'single nucleotide polymorphisms' (SNPs) are markers that can allow epidemiologists to uncover the genetic basis of many diseases. They can also provide information about our personal responses to medicines — in this way, the pharmaceutical industry will get new targets and new tools to sharpen drug specificity. Moreover, the analysis of SNPs will provide us with the power to uncover the genetic basis of our individual capabilities such as mathematical ability, memory, physical coordination, and even, perhaps, creativity."

Moses: What do you mean by "was the dream"?

Socrates: In the excitement to test those predictions, many Genome-Wide Association Studies (GWAS) were conducted over the ensuing decades to see whether SNP's, which are the markers for gene variants, could be identified that conferred an increased risk of common diseases, like atherosclerosis, diabetes, hypertension, Alzheimer's disease, and so forth. Predictive SNP's were discovered, but unfortunately they predicted only a modestly increased risk for those diseases. The average increase in risk was only about

[92] Nobel Laureate **David Baltimore**, *Nature* 409, 814-816, 2001.

30%, and typically explained less than 20% of the genetic component [93]. Compare that to just asking a patient about risk factors like smoking, diabetes, family history, cholesterol or hypertension. If they say yes to all of them, it predicts a 300-400% increased risk of cardiovascular disease.

Moses: Why? I thought that your genes play a huge role in your health.

Socrates: They do, but the common diseases that account for the vast majority of the total human disease burden aren't caused by a single defective gene. They are caused by a large number of different genes interacting together with the environment. Individually, each of those genes contributes only a small amount of the risk. From the GWAS results, it's been estimated that hundreds or thousands of gene variants may be involved and that their individual effect sizes are too weak to be identified individually by GWAS. And even if you could identify all of the gene variants involved, developing a therapy to replace hundreds or thousands with normal genes would be a technical impossibility.

Moses: But what about all the headlines that you read, announcing that this gene or that gene has been identified as the cause of some disease?

Socrates: Those are genuine headline-worthy discoveries. But the reality is that they refer mainly to monogenic diseases caused by a single abnormal gene, like cystic fibrosis, familial hypercholesterolemia, hypertrophic cardiomyopathy or hereditary arrhythmia syndromes, to name just a few. Monogenic diseases are much rarer than polygenic diseases, and generally affect less than one in a thousand people. Even if you could cure all of those diseases by replacing the defective gene, it would impact only a few percent of the total disease burden for humans worldwide.

Moses: Even if it isn't practical to replace hundreds or thousands of genes to cure common diseases, why can't we at least identify all of the genes that are important? Instead of looking for correlations between one SNP and a disease, can't you analyze pairs or triplets or even much larger combinations of SNP's to see which combinations correlate strongly with a disease?

Socrates: It's a numbers game, I'm afraid. There are roughly a million SNPs in the human population that occur in more than 1-2% of the population. That means that identifying single SNP that correlates strongly with a disease is already a one-in-a-million shot. But if you have a million SNP's, then the number of possible SNP pairs is almost a trillion, and the number of possible SNP triplets is around a million trillion. By the time that you get to 16 SNP's, the total number of possible combinations exceeds 10^{80}. Remember that number?

Moses: Yeah, you mentioned it before – it's the estimated total number of atoms in the observable universe.

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[93] **T. Manolio**. Genome-wide Association Studies and Assessment of the Risk of Disease. *N Engl J Med* 363:166-76, 2010.

Socrates: Exactly. So the odds are much worse than finding a needle in a haystack. It's like trying to find one atom in the universe!

Moses: Any way around it?

Socrates: That's precisely why scientists have become so interested in applying network theory to biology, to figure out what's going on inside the black box in those highly interconnected scale-free networks, like gene networks (Figure 10-6).

Moses: You mean for the "black box calculus" that we were talking about before?

Socrates: That's the goal. For instance, take the one hundred or so inbred mouse strains in which Jake and his colleagues compared the levels of the 8,000 genes expressed in heart tissue. To the naked eye, the gene expression levels appeared to vary randomly from strain-to-strain (Figure 13-3, top panel). However, using an unsupervised machine learning algorithm to look for patterns in the data, they detected a hidden order, indicating that the gene expression levels were regulated in a coordinated way. That allowed them to group the 8,000 genes into about 20 separate modules.

Moses: How?

Socrates: Say that you compare the expression levels of two genes, A and B, in all of the different mouse strains. If you find that for every strain in which the expression level of gene A is low, the corresponding expression level of gene B is also low, and vice versa, that means that the two genes are correlated. If that correlation holds throughout all one hundred strains, then genes A and B can be assigned to the same gene co-expression module. But suppose the expression level of another gene C is uncorrelated with genes A and B, but is highly correlated with gene D. Then genes C and D are assigned to a different gene co-expression module. When Jake and his colleagues used their algorithm to analyze all 8,000 genes that way, the algorithm grouped the 8,000 genes into about 20 gene co-expression modules, with each module

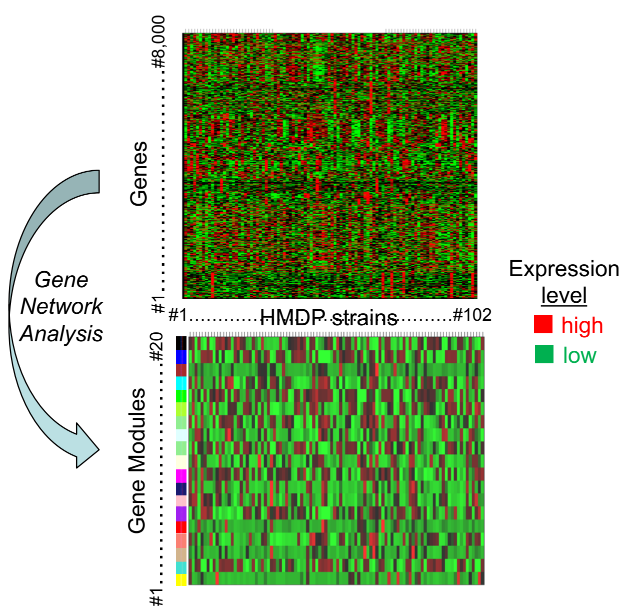

Figure 13-3. Gene expression levels (upper) and gene module expression levels (lower) in heart tissue from 102 different strains of HMDP mice showing marked variation between strains. Using gene network analysis, 8,000 genes expressed at high levels in the heart were condensed into 20 gene modules in each strain. Courtesy of Jake Lusis and Yibin Wang.

typically containing tens to hundreds of genes.

Moses: Did the expression levels of the gene modules differ widely from strain-to-strain, similar to the way that individual gene expression levels did?

Socrates: Indeed, that's exactly what they found (Figure 13-3).

Moses: How does that help?

Socrates: Because just like they could test whether the expression level of a single gene correlated with the susceptibility to an imposed stress, now they could also test whether the expression level of a gene module, containing tens to hundreds of genes, correlated with the susceptibility to the stress.

Moses: Did it work?

Socrates: Yes. For the stress causing heart failure, for example, a whole group of genes in one particular module showed a much stronger correlation with susceptibility to heart failure than did any single gene. So instead of a GWAS, they called the method GMAS, for Gene Module Association Study.

Moses: Fascinating. Presumably the genes in that gene module were causing the heart failure, correct?

Socrates: That still remains to be determined. The expression levels of genes in that gene module correlated with susceptibility to heart failure, but correlation is not the same as causation. To prove causation, you need to have a way to raise or lower the expression level of that gene module and show that it causes the heart failure to become better or worse.

Moses: How do you do that?

Socrates: So far, no one really knows. It's not yet clear what controls the expression level of the gene modules identified by network algorithms. Most likely, the answer is buried somewhere in our junk DNA.

Moses: You mean the non-coding DNA that isn't translated into proteins?

Socrates: Exactly. Only about 2% of the DNA in our chromosomes codes for proteins. The other 98% is non-coding DNA whose function is mostly unknown, which is why it has been called junk DNA. But about 80% of this so-called junk DNA has been shown to be biochemically active, and at least some it is transcribed into RNA that binds to DNA to regulate gene expression.

Moses: So non-coding DNA feeds back to regulate expression of coding DNA? Is that how genes are turned off and turned on in different tissues?

Socrates: It's one way, but not the only way. There are also coding genes that make proteins called transcription factors that bind to DNA to regulate the expression of different genes. Then there are some coding genes that make protein enzymes that chemically modify DNA, for example by acetylation or methylation, which affects gene expression. In other words, there's genetic feedback regulating gene expression at many levels. Feedback upon feedback – that's part of what makes it a black box.

Moses: Does that mean that common polygenic diseases, which account for the vast majority of human diseases like hypertension, atherosclerosis, Alzheimer's disease, etc., might be caused by mutations in the genes that regulate gene modules, rather than mutations that affect the function of specific proteins like in the rare monogenic diseases?

Socrates: It's a definite possibility. All the proteins in an individual organism can be completely normal, but if they are not expressed in the right proportions, they can result in a disease. That's not really very surprising, since we already know that the same genes expressed differently can result in a completely different phenotype. Remember, a caterpillar and a butterfly are the identical set of genes, just expressed differently (Figure 13-4). And the caterpillar and butterfly also have obviously different environmental susceptibilities – a caterpillar is more likely to drown in a flood than a butterfly who can fly away.

Moses: What you saying is that if genotypes are really Good Enough Solutions that exhibit different susceptibility to environmental challenges, then it doesn't necessarily make sense to look just for mutations in coding genes as the cause of common diseases – the proteins could all be completely normal and the disease caused by mutations in non-coding genes that regulate the expression of gene modules.

Figure 13-4. The caterpillar and the moth - identical genotypes, different phenotypes.

Socrates: Indeed, based on what's been learned from the mouse strains and other similar genetic resources, that could well be the case. Different strains have different susceptibilities to obesity, atherosclerosis and heart failure due to their genetic differences. But the proteins made by those genes all seem to function normally. So the different susceptibilities must be related to the different expression levels of the genes – i.e. to genes that regulate gene expression.

Moses: The black box really is a lot more complicated in biology than in deep learning algorithms, isn't it?

Socrates: Very true. In fact, so complicated that it's hard to even judge whether methods of constructing gene networks are valid, especially when different methods produce different results. That's the real challenge – how to figure out what's really going on in the black box of hidden layers when everything feeds back to affect everything else.

Moses: Ah yes, back to our sorely-needed "black box calculus." Maybe the answer is to start simple, and then gradually incorporate more complexity. Perhaps artificial deep learning neural networks or other machine learning approaches could be used as tools to figure out the best ways to analyze what's going on inside the black box.

Socrates: Not a bad idea. The problem in genomic learning is that we know the input layer (genotype) and the output layer (phenotype), but we don't know what's going on inside the black box. On the other hand, once you've trained a deep learning algorithm, you have a complete knowledge of the architecture and weightings and biases of the hidden layers that convert the input into the correct output.

Moses: So why don't we start with an artificial deep learning algorithm about which we have complete information about the input, hidden layers and output. Then from the input and output, we could test different network analysis methods to see if any of them can predict the architecture and weightings and biases of the hidden layers inside the "black box." If we are successful at validating a reliable method for analyzing the "black box", then we could make the algorithm gradually more complex by adding feedback loops within and between the hidden layers. At each step, we validate which network analysis algorithms work best as the complexity of the algorithm gradually increases to resemble more and more realistically the real thing - genomic learning in biology.

Socrates: A very thoughtful approach, Moses! You should suggest it to your colleagues. Maybe one of them can use it to invent the "black box calculus" that is so desperately needed. That should be worth a Nobel prize or two, at the very least.

CHAPTER 14: The Selfish Genome

Moses: Maybe there's some hope after all. Still, there's one aspect about this genomic learning algorithm that really bothers me.

Socrates: What's that?

Moses: In the end, it seems to imply that none of us really matter as individuals. We are just the pawns of an impersonal genome that perpetuates itself by pitting us against each other - spitting out new phenotypes and then having us fight it out to see who survives, keeping the strongest and discarding the weakest. That's what genetic optimization really means.

Socrates: The Selfish Gene [94], as Richard called it.

Moses: It's a pretty depressing state of affairs if you ask me.

Socrates: Really, what choice does your genome have? If you think about it, the genome is in the same boat as you are. You could call it the Selfish Genome. Your human genome has to fight it out with the sea lion genome and all the other genomes in order to carve out its place in the biosphere. Genotypes compete against genotypes, genomes compete against genomes, and only the fittest survive. Same principle operating at different scales. Nature likes that kind of bottom-up approach, repeating simple principles over and over again at increasingly complex scales. So you may feel like a pawn of your genome, but your genome is a pawn too.

Moses: A pawn of what exactly?

Socrates: Of life in general. The way that I see it, there's really only ever been one living organism on the planet earth, born about 3.5 billion years ago – a genomic learning algorithm driven by genetic optimization, whose prime directive is "Survive at all costs." Or, in biblical terms, "Be fruitful and multiply."

Moses: What are you talking about?

Socrates: That's when the first self-replicating nucleotides started replicating. Ever since, that same genomic learning algorithm has just been continuously morphing into whatever form allows it to survive in any habitable environment anywhere - on land, sea or air. The human species is just one of its many diverse manifestations. I know how much you humans prize your individuality, and like to think of yourselves as superior to other lifeforms, but nature has a broader perspective.

Moses: Now you sound like a computer scientist - that all of life can be reduced to a universal genomic learning machine like some mastermind deep learning neuroevolution algorithm.

Socrates: That's one of the big advantages of replacing gradient descent with genetic optimization, remember? Not only can it optimize the weights and biases in the original

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[94] **Richard Dawkins**. The Selfish Gene. Oxford University Press, 1976.

neural network architecture, but it can also optimize the architecture itself, adding or removing more hidden layers of interconnected nodes and links, whatever is required to adapt. It's that plasticity that gives genetic optimization the open-ended ability to evolve and adapt to whatever a new environment may require.

Moses: Actually, that also sounds very familiar to the formula that gives biological networks their scale-free small-world properties: random interactions, growth and preferential attachment.

Socrates: Indeed, it's no coincidence. That's what life is - a growing system of nodes and links that interact randomly, but whose architecture is shaped by a genetic optimization algorithm that preferentially attaches new nodes to already highly established nodes. Et voilá, there you have it – a network of layered scale-free, small world networks as the basis of life! Life with a capital L, first emerging in the primordial seas as archeae and bacteria and evolving from single cells to multicellular organisms, invertebrates to vertebrates, reptiles to birds to mammals, mammals to primates to humans. And who knows what the future will hold!

Moses: A march towards the ultimate genome ideally optimized to survive on the planet earth, with *homo sapiens* at the vanguard (Figure 14-1A), I suppose.

Socrates: I seriously doubt it. The goal of life is not to achieve some "ultimate genome ideally suited to survive on planet earth". It's just the opposite – to achieve maximum diversity, so that Life with a capital L can survive anything that nature throws at it. Evolution isn't a straight line (Figure 14-1A) – it's more like an ever-expanding circle (Figure 14-1B). It started as a small dot with the first lifeforms and has expanded into a large circle over the last 3.5 billion years, populated by a rich diversity of genomes adapted to almost every conceivable environmental niche on the earth. That's what gives life its resiliency.

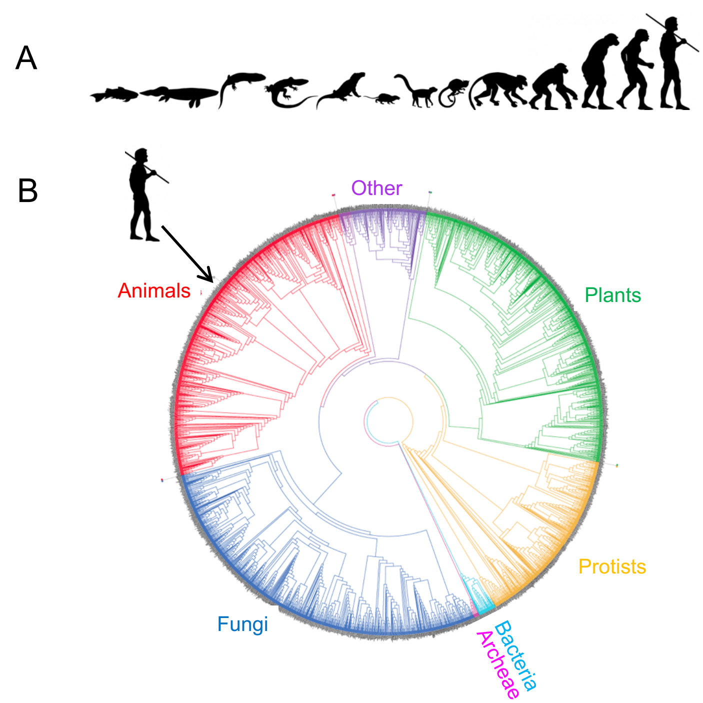

Figure 14-1. A. Naïve linear view of evolution from fish to man. **B. More correct view of evolution** as an expanding circle over time. Center is at the origin of Life 3.5 billion years ago, outer circumference is present era.

Moses: So you're saying that in the end, adaptability rules, not perfection. And adaptability depends on genetic diversity.

Socrates: Exactly - the more Good Enough Solutions, the merrier! Just like individual genotypes are each Good Enough Solutions that help a specie's genome survive, the genomes represent the Good Enough Solutions that life needs to survive, each adapted to its own ecological niche in the Biosphere. That diversity that makes it very unlikely that any one calamity could wipe out all of life at once. There have been many mass extinctions in the history of the world, but so far life has always rebounded, thanks to its diversity!

Moses: So you don't think that the human genome has a special place in life, even though we dominate all other species on planet earth?

Socrates: I know that you humans like to think of yourselves as the crowning achievement of evolution, but dominating other species does not make you superior.

Moses: Why not?

Socrates: From the standpoint of evolution, 'superior' means one thing only – more fit to survive in a specific environment.

Moses: And you don't think that we're more fit to survive than any other lifeform?

Socrates: I don't think that you'd fare nearly as well as a chimpanzee if someone dropped you butt naked in the middle of a jungle. Not to mention that a chimpanzee, like any other mammal even close to your size, is much stronger, more agile and more ferocious than you – one-on-one, you wouldn't stand a chance in hand-to-hand combat. As for being superior to a sea lion, how long do you think you could swim if I dropped you in the middle of the ocean?

Moses: I see your point. Even though humans are more intelligent than chimpanzees, chimpanzees are physically much stronger. So we are superior in some ways, and they are superior in others. Same for sea lions. We're better adapted to survive in our environment, and they're better adapted to survive in theirs.

Socrates: Exactly. It's not like chimpanzees, or sea lions for that matter, are more primitive lifeforms than you. Humans didn't evolve *from* chimpanzees. Both of you evolved from a common ancestor who lived four to eight million years ago, and most certainly bared little direct resemblance to either of you now. Since then, both of your genomes evolved independently to match the environments that you currently inhabit. The main difference is that humans have a much greater capacity to reshape their environment than do chimpanzees! Which is not to say, however, that you are reshaping your environment for the better, either for yourselves or chimpanzees, much less for the rest of the Biosphere!

Moses: Yes, I see your point. Humanity does seem to be causing more destruction than preservation of the ecosphere these days. Still, it's a bit disappointing to think that life's only goal is just to get by and survive by maximizing genomic diversity, with no grander purpose than that. For humans, it's important to believe that life has some ultimate purpose after all. Otherwise, what's the point of living?

Socrates: If you're a God-centered person, then I suppose that you can believe that serving God is your purpose in life.

Moses: And if you're not God-centered, what then?

Socrates: There's a still solid scientific explanation for you to fall back on.

Moses: What's that?

Socrates: The obvious one, that genetic optimization selects against humans who believe that the life has no purpose worth living for. If a person is too depressed to procreate or decides to end it all by committing suicide, then the "life has no purpose" gene variants that predispose to that behavior will not make it through to the next generation. Your genome prefers to keep the "optimistic" gene variants that give you the strength to bear the slings and arrows of outrageous fortune, so-to-speak. So thanks to your genome, your optimism that life has some ultimate purpose is inherently self-reinforcing!

Moses: That sounds like we're being tricked by genetic optimization into thinking that life must have a purpose. That's even more depressing than not having an explanation!

Socrates: It may not be very spiritually satisfying, I have to admit. But why do you need to have an answer for everything?   Can't you just accept life as a blessing, and leave it there? We already agreed that there are things about the universe that are unknowable to us through scientific reasoning. Perhaps the ultimate purpose of life falls into that category.

Moses: Still, if you believe in science, then it's very frustrating to relegate the purpose of life to the unknowable category.

Socrates: I feel your pain.

Moses: Thanks, but that doesn't really help.

Socrates: Take heart, maybe someday you will figure it out someday through science – I'd be the last one to discourage you from trying. And even if it turns out the humans don't have the capability to grasp life's ultimate purpose, that doesn't mean that a purpose doesn't exist. Would you like to know how I think about it?

Moses: Sure.

Socrates: Imagine you are one of the cells beating in your heart.

Moses: What does that have to do with the purpose of life?

Socrates: Bear with me. Each of your heart muscle cells shortens by about 15% or so with each contraction. Yet when all of the heart cells contract together, the heart ejects more than 50% of the blood in the ventricles – in other words, the whole is greater than the sum of the parts [95]. An obvious winner as far as the organism's survival is concerned, since if your heart cells didn't beat effectively together, they wouldn't generate a blood pressure. With no blood pressure, your heart would die and you'd die along with it!

Moses: What keeps heart cells in synchrony with the each other?

Socrates: A pacemaker located in the upper chambers of the heart, where the right atrium joins the superior vena cava, called the sinus node. It generates a voltage signal that propagates through the various regions of the heart, causing the heart cells in the ventricles to contract synchronously to eject more than 50% of the blood and generate the blood pressure during each heartbeat.

Moses: Fascinating, but how is this related to the purpose of life?

Socrates: Be patient, I'm getting there. Suppose one of the heart cells in your ventricles had the ability to reason like you. How do you think it would feel about being coerced to beat once a second, every minute of every day? From its perspective, a heart cell is stuck in one location in the heart tissue and all that it can observe is that each of its neighbors are marching in lock step with some far away pacemaker, forced to shorten by 15%, second after second, with no letup, and to no obvious point. How could it appreciate that the combined synchronous shortening of all its neighbors, each contributing a meager 15%, creates an efficient pumping mechanism that ejects more than 50% of the blood in the heart on each heartbeat?

Moses: It couldn't, I guess.

Socrates: Exactly, because it's trapped in Plato's Cave. From its limited vantage point in the tissue, it can't emerge into the sunlight to see that it is a part of something greater than itself. It has no way to appreciate that its mundane repetitive shortening is creating a whole much greater than the sum of the parts.

Moses: But even if it could move beyond the boundaries of the heart itself, and see that the purpose of the heart is to eject blood, it still might conclude, 'Who cares? Blood comes in, and we pump it out, what's the point?'

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[95] The heart's ability to achive a 50% ejection fraction is due to the *nonlinear* way in which the cells are geometrically arranged. If the heart cells were lined up end-to-end, then the whole would just be the sum of the parts, and the line of cells would by shorten by 15% of its total length. But if the ends of the cable are linked together to form a circle instead of a line, the circumference still only shortens by 15%, but the area enclosed by the circle (πr^2) decreases by 28% (0.85x0.85=0.72). And if the cells are arranged to cover the surface of a sphere, the volume of the sphere ($4/3\pi r^3$) would decrease by 39% (0.85x0.85x0.85=0.61), ejecting close to 40% of the blood when the cells shortened by just 15%. In addition, because the cells are mostly made up mostly of incompressible water, the total volume of each heart cell remains constant. That means when the cell shortens in length, it must thicken to keep the total volume the same. Thus, when the outer circumference of the intact whole heart shrinks by 15%, the inner diameter has to shrink by more than 15% to accommodate the fatter width of the cells. That makes the chamber volume shrink by more than 50%, so that more than 50% of the blood in the chamber is ejected with each beat.

Socrates: True, but if the heart cell could see beyond the heart to the next level, it would see that the heart is pumping the blood not only for itself, but for all of the other organs in the body to keep the whole organism alive. And why stop there? The organism in question is also part of something greater than itself, namely the human race, which, in turn, is part of something greater than itself, the animal kingdom, which is part of something greater than itself, the Biosphere, and so on and so on!

Moses: And your point?

Socrates: My point is that at each of those more integrated levels, new properties emerge that make the new whole greater than the sum of the parts. But our poor heart cell, encased in the ventricle, has no real chance to appreciate the significance of what it's doing! Even if it did have a brain of its own, how could it possibly appreciate, from its restricted vantage point, the useful consequences at the more integrated level of the heart, much less at the level of the whole organism.

Moses: That's true, I guess. A heart cell cannot appreciate its ultimate purpose as well as we can.

Socrates: Exactly. But here's the real question - ultimately, are we any better off?

Moses: What do you mean?

Socrates: As a human being, you can pity the heart cell for not being able to appreciate that its meager 15% shortening is translated into a useful function at the more integrated level of the heart. And you can also see that the heart's pumping is being translated into an essential function for the all the organs in your body. But after that, you're pretty much in the same boat as the heart cell. So what if your heart cells are fulfilling an essential purpose in helping humans to survive? In the larger scheme of the universe, why is it important for you or me to survive, or for our genomes to survive, or for a universal genomic learning algorithm or biosphere or solar system or the universe itself to survive? We may be a few steps ahead of our heart cells, but ultimately, neither we nor our heart cells are in a position to understand the ultimate point of it all.

Moses: I thought you were going to give me an uplifting reason to have faith that there is an ultimate purpose to it all. How is this supposed to help?

Socrates: Be patient. So far, I'm just reiterating what Plato articulated so poignantly several thousand years ago - that it's difficult to see much beyond the limits of your particular Cave. You can see deeper into your own Cave, to understand the purpose of the less integrated scales like the heart cell and the heart. But it's much more challenging to see out into the sunlight of more advanced levels of integration.

Moses: What you're really saying is that it's easier for the 'whole' to understand the 'parts', than for the 'parts' to comprehend the 'whole'.

Socrates: Exactly. You can intuitively appreciate the purpose of your parts that you're made of. But the emergent properties of the next levels are conceptually different from anything at your own level. That makes it hard to understand the ultimate purpose of more highly integrated levels, unless you already know what you're looking for.

Moses: So if we go back to our heart cell, it can only shorten by 15%, but the heart empties more than 50% of the blood on each beat. And even if the heart cell could reason, it would have no perspective, when it's trapped at one location in the heart, to conceptualize how this happens.

Socrates: Just like you and your fellow human beings don't have the perspective to comprehend the ultimate purpose that humanity serves in the universe.

Moses: So then what's the point of it all? You're not helping.

Socrates: Don't take it so hard. It's obvious that you are serving a useful purpose, even if you can't fully comprehend it.

Moses: How so?

Socrates: By extrapolation. You can see that your heart cell serves a useful purpose to your heart, and your heart serves a useful purpose to your body, and your body serves a useful purpose that allows you to contribute to the well-being of human society. So think of natural selection and genetic optimization as the quality control mechanisms ensuring that only qualities that serve a useful purpose for something greater than themselves are preserved. So as long as human beings serve a useful purpose in the biosphere, planet earth, solar system and universe, they will survive. If not, they will perish and be replaced by the next candidate for nature's crowning achievement. Of course, the hooker is that none of us may never know what our ultimate purpose is, or even how to go about figuring it out. But if all the parts that we are made of serve a useful purpose, we can inductively reason that we probably also serve a useful purpose, as part of something greater than ourselves, even if we can't know ultimately what that is. We just have to accept that the universe works in strange ways.

Moses: And you think all living things can all be accounted for by just an accumulation of networks piled on networks, driven forward by the new emergent properties that arise by chance with each new combination. And all this has spontaneously self-organized itself? And we just have to have FAITH that it serves some ultimately high purpose?

Socrates: Why not believe that the purpose is ultimately good, rather than bad or meaningless? If you weren't part of something greater than yourself, then the chances are that genetic optimization would have eliminated you long ago. You are the living proof of your own usefulness!

Moses: Living proof of our own usefulness – now that seems like circular reasoning.

Socrates: Life is circular – birth, death, birth, death….. Do you really need to know the purpose of life in order to motivate yourself to go on living? And suppose you found the purpose of life - then you'd have a real reason to be depressed.

Moses: What do you mean?

Socrates: If you really knew the ultimate purpose of life, what would be left for you to discover? The mystery of life solved – you might as well hang it up once you know that. Be careful what you wish for.

Moses: Maybe our purpose in life is to seek the purpose of life, whether we achieve it or not.

Socrates: There you go, that's much a healthier attitude! It's the journey not the destination that's important. And whether you find it or not, it is and will always be the noblest of quests - the philosopher's dream!

Moses: I suppose you're right. I feel better. Do any other animal species torture themselves with these questions?

Socrates: Not that I'm aware of. That's the one quality that earns you a special place in the animal kingdom - your superior logical reasoning abilities compared to any other species. But, like everything else in nature, it's Yin and Yang - the key to your success is also what ties you up in knots.

Moses: Our ability to torture ourselves with logical reasoning?

Socrates: Haven't we just demonstrated that? First you were depressed because we reasoned that life had no discernable ultimate purpose, and then you were uplifted by reasoning that the ultimate purpose of life was to search for the ultimate purpose of life! Reason can dig you into a hole or dig you out of it, depending on which premises you choose to derive your conclusions from!

Moses: You make it sound like logical reasoning can be used to justify anything. If that were true, reasoning would be pretty useless.

Socrates: Not really. We've discussed it before – in logical reasoning, the validity of the conclusions depends the validity of the premises. Some premises are valid, others are not. In most of physics and chemistry and to lesser extent biology, you can tell the difference by performing experiments to validate whether predictions of your premises are actually observed or not. Used that way, logical reasoning guided by experimental validation has transformed human society through technology, from the invention of the wheel to machines to computers and AI. But life is inherently more complex especially at highly integrated levels like social behavior. Using logical reasoning to guide human behavior is fraught with peril, because it's hard to know which premises are truly valid and which are not. That's the rub. Like deciding whether the appropriate premise for resolving a conflict is "an eye for an eye" or "turn the other cheek." Your genome doesn't really care – if one human community makes the wrong choice and self-destructs, chances are that there's another community that will make the right choice and carry on. The power of genetic diversity once more – it applies to communities as well as individuals!

Moses: I see your point. A lot of wickedness in human affairs has been rationalized based on faulty premises.

Socrates: The specialty of demagogues around the world! And the source of man's inhumanity to man. When your species traded brawn for brains, the ability to use logical reasoning to develop technologies like weapons gave you a huge competitive advantage over other genomes. But it also gave you competitive advantages against each other – the power to use logical reasoning based on valid premises to develop superior weapons to vanquish your rivals, and the power to use logical reasoning based on false premises to deceive your rivals. You can't help it – competition with each other is hard-wired into your genes. Genetic optimization means that only the fittest will survive, whether it's a fair fight or the result of underhanded treachery!

PART III: Humanity

The Garden of Eden

The Garden of Eden, where we hunted and gathered
A couple of hours a day, all that we needed to sustain ourselves.
We frolicked the rest of the time,
Playing, fighting, laughing, crying, loving,
Contemplating the great mysteries of the universe,
As we roamed freely from here to there and back again.
Life was brief, but healthy and complete,
When we shared everything in the Garden of Eden.

Until the serpent tempted us to eat the apple from his orchard.
He sweet-talked us, "Just water the orchard and the apples will appear."
So we did, and we were fruitful and multiplied
And traded our innocent life for working from dawn to dusk,
To keep the apples growing as our numbers ever increased.
We divided the land, the labor, and kept track of who contributed what,
Created rights to property, so our children could inherit the fruits of our labor,
Dividing ourselves into rulers and followers, masters and slaves,
Haves and have-nots,
Instead of sharing everything,
Like we did in the Garden of Eden.

And here we are now, more than seven billion strong,
Succeeding materially beyond our wildest dreams,
Working twelve hours a day just to stay in place.
Even though we can't keep up.
Not enough food or water or shelter,
Or education or healthcare for all of us,
So many starving without hope, most struggling just to stay afloat
While the few squander immense wealth and property.
The poor get poorer and the rich get richer,
Instead of sharing everything,
Like we did in the Garden of Eden.

CHAPTER 15: The Evolution of Reasoning

Moses: I suppose that reasoning can be used for good or bad purposes, like anything else. But, for better or for worse, it's our capacity to reason that has allowed humans to dominate the rest of the animal kingdom, don't you think? That's what sets us apart from all other species.

Socrates: Like a gift from God?

Moses: I wouldn't go that far. It must have evolved by natural selection, like everything else.

Socrates: How?

Moses: I suppose it evolved to help humans make more intelligent decisions. A person who reasons well will make wiser choices than a person who doesn't. That's obviously a fitness advantage that natural selection should reward, don't you think?

Socrates: I think it's a bit more nuanced than that.

Moses: What do you mean?

Socrates: If that were true, then humans should be much better at reasoning than they actually are.

Moses: What do you mean? How could humans be bad at reasoning if it's the key to our evolutionary success?

Socrates: Because that's what the evidence shows.

Moses: What evidence?

Socrates: Let's start with other animals first. All animals have to make decisions, right? So how do they do it?

Moses: Since they can't reason very well, their only choice is to rely on intuition.

Socrates: Driven by?

Moses: Instinct and emotion.

Socrates: Exactly. If an animal spots a dangerous predator nearby, its brain makes an association between the predator and the danger/fear emotion, and infers intuitively that the proper course of action is to flee as expeditiously as possible. It's empirical pattern recognition, like a machine learning algorithm that's been trained to recognize a pattern and respond reflexively. The animal doesn't rationally consider the pros and cons before deciding. If it did, it would become dinner. Does that apply to humans too?

Moses: Of course. Humans also react intuitively to imminent danger. It's essential for survival in dangerous situations. But the difference is that when there's time to deliberate before making a decision, humans have the ability to use logical reasoning rather than to rely on instinct alone.

Socrates: You are absolutely correct. Daniel [96] referred to the first type of decision-making based on intuition as *fast thinking*, and the second type of decision-making based on reasoning as *slow thinking*. They are also called Type 1 and Type 2 thinking.

Moses: It makes perfect sense to me. Then humans can rely on the intuitive Type 1 *fast thinking* mode when they need to make an immediate, instinctive decision, like avoiding a predator or dangerous situation, and the rational Type 2 *slow thinking* mode when they have time to deliberate and consider all the options before making a decision.

Socrates: That's what you would think. But actually, that's not what happens.

Moses: Why not?

Socrates: Because the evidence shows that even when people have plenty of time to deliberate before making a decision, they don't go to the *slow thinking* mode right away. They still rely on *fast thinking* to form an intuitive opinion first, and the *slow thinking* comes afterwards.

Moses: Does it really matter? As long as the *slow thinking* gives you a chance to weigh the pros and cons evenly and reject your initial intuitive *fast thinking* decision if it was faulty, you'll still end up making the better decision.

Socrates: You'd be right if a person carefully weighed the pros and cons in a balanced fashion before making the final decision. But what Daniel found is that once people make the intuitive decision using the *fast thinking* mode, they are good at coming up with reasons supporting their decision, but poor at coming up with counterarguments against it. It's called *confirmation bias.* In other words, as individuals, people don't seem to be very good at unbiased reasoning when they switch from the *fast* to the *slow thinking* mode.

Moses: That's hard to believe. After all, humans owe everything to reasoning. It's the basis of all the science and technology, the key that's given humans the upper hand over the rest of the animal kingdom!

Socrates: I agree. That's exactly why it's so surprising that as individuals, people are so bad at reasoning. Since natural selection works most powerfully at the level of the individual, you'd think that if reasoning had evolved to improve decision-making, individuals would be better at it and not consistently make simple logical errors.

Moses: So what exactly is this evidence that individual humans are so bad at reasoning?

Socrates: Ever heard of the Wason selection task?

Moses: No, what's that?

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[96] **Daniel Kahneman** (b. 1934), an Israeli-American psychologist, is notable for his pioneering work on the psychology of judgment and decision-making, as well as behavioral economics, for which he was awarded the 2002 Nobel Prize. In 2012, his book *Thinking, Fast and Slow*, which summarizes much of his research, was published and became a best seller. He is professor emeritus of psychology and public affairs at Princeton University's Woodrow Wilson School.

Socrates: A test that Peter[97] invented in 1965 to understand why people consistently make simple logical mistakes in reasoning.

Moses: How does it go?

Socrates: The most common version is called the four card selection task. An examiner places four cards a table and informs the subject that each card has a letter on one side and a number on the other side. For example, the face-up sides of the cards might show *E, K, 2* and *7* (Figure 15-1). The examiner then asks which cards must be turned over to prove whether or not the cards obey the following Rule: *If there is an E on one side, then there must be a two on the other side?* Go ahead, give it a try. Take as much time as you like.

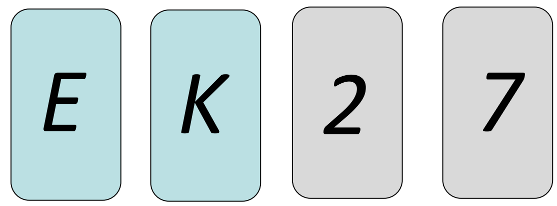

Figure 15-1. Wason 4-card selection task. Each card has a letter on one side and a number on the other side. What cards must be turned over to prove whether or not the cards shown obey the rule: *Every card with an E on one side has a two on the other side*?

Moses: Hmmm…..I'd say the *E* card and the two card.

Socrates: Why?

Moses: Because if you turn over the *E* card and there is a two on the other side, it validates the Rule, and if not, it violates the Rule. And if you turn over the *2* card and find an *E* on the other side, it further confirms the Rule.

Socrates: And what about the *K* and the *7*?

Moses: They don't seem as relevant.

Socrates: You and 90% of people think the same way. Unfortunately, you are wrong.

Moses: Why?

Socrates: Let's go through the cards one by one. Your choice of the *E* card is correct, because if you turn it over and there is a two on the other side, it validates the Rule, and if not, it violates the Rule, just like you said. But your choice of the *2* card is really not helpful, because the Rule, as explicitly stated, does not claim that if there is a *2* on one side, there must be an *E* on the other side. So if you turn the *2* card over and find a different letter than *E,* the Rule is not violated. If you turn it over and find an *E,* that's

[97] **Peter Cathcart Wason** (1924 –2003), a cognitive psychologist at University College, London, pioneered the psychology of reasoning, and why people make certain consistent mistakes in logical reasoning. He designed problems and tests to demonstrate these processes, including the Wason selection task (P.C. Wason, "Reasoning" in B.M. Foss. *New Horizons in Psychology*. Harmondsworth Penguin, 1966.). He coined the term "confirmation bias" to describe the tendency for people to immediately favor information that validates their preconceptions, hypotheses and personal beliefs regardless of whether they are true or not.

okay too. Either way, it doesn't give you any useful information about whether the Rule is true or false.

Moses: Sure, but what if you reshuffled the cards, and now the *2* is face-down instead of face-up?

Socrates: It still doesn't help prove or disprove the Rule. Say there was an *E* on the other side of the *2* card, so that now the *E* is face-up. When you turn over the *E* card, there would be a *2* on other side, consistent with the Rule. But if there was another letter instead, the *2* would still be fine, since the Rule doesn't exclude other letters from having a *2* on the other side.

Moses: So then which other cards would you turn over to prove or disprove the Rule?

Socrates: Let's keep going and find out. The *K* card is next. What do you think?

Moses: I guess it won't matter whether the number on the other side is a *2* or a different number.

Socrates: Correct, either is consistent with the Rule. And finally, how about the *7* card? Say you turn it over and there is an *R* on the other side.

Moses: That would be consistent with the Rule.

Socrates: And what if you turn it over and there is an *E* on the other side?

Moses: Ah, now I get it! If the *7* card has an *E* on the other side, then the Rule would be violated. That means that the two critical cards to prove whether the Rule is true or false are the *E* and the *7* cards, not the *E* and the *2* cards

Socrates: There you go - with a little coaching, you figured it out!

Moses: So only 10% of people pick the *E* and the *7* cards, and everyone else gets it wrong?

Socrates: That's correct. There are many other versions of the selection task, and the outcomes are very consistent. The majority of people, even professional scientists trained to think logically, usually get it wrong. And the way that they get it wrong is quite instructive about *fast* and *slow thinking*.

Moses: What do you mean?

Socrates: Let's analyze your performance just now. Even though I told you to take as much time as you needed, you gave me your answer rather quickly, perhaps to impress me with how clever you are, or because you didn't want to make me wait out of politeness. Either way, you used the *fast thinking* mode. Since the Rule involves the letter *E* and the number *2*, you intuitively inferred that those cards must be the most relevant to proving the Rule true or false. Then, when I asked you why you choose those particular cards, you switched to the *slow thinking* mode to come up with reasons. Although you came up with the correct reason for selecting the *E* card, you gave me a faulty reason for choosing the *2* card. Even when I gave you the opportunity to think about it, you still didn't come up with the counterargument against picking the

2 card until I pointed it out to you. You also didn't methodically analyze the pros and cons of picking the *K* or the *7* cards, because you had already dismissed their importance based on your *fast thinking* intuition. That's classic *confirmation bias*, just like Daniel described.

Moses: It doesn't bode very well if people make decisions by intuition and only retroactively come up with one-sided biased reasons to support them. That makes reasoning sound like window-dressing – mere self-justification after the fact. How does that provide any advantage over just relying on intuitive *fast thinking* decisions like other animals do?

Socrates: Since humans evolved from animals, does it really surprise you that your primary mechanism of decision-making is *fast thinking*? A lot decisions have to be made very quickly, like fight or flight reactions. If you have to come up with conscious reasons in order to decide whether or not to flee from a tiger, you'd be dinner before you took your first step.

Moses: Sure, that part makes sense. But when it's not a life-or-death situation, like the four card Wason task that I just failed, why did I still use *fast thinking* first, instead of going directly to *slow thinking*?

Socrates: Here's a clue. When I asked you to tell me the reasons for your choices, you tried to convince me that your initial decision was correct, instead of using the opportunity to go back and systematically re-think through each card to see if you'd missed something, like we did together afterwards.

Moses: That's because I thought I was right.

Socrates: Exactly my point. You thought you were right based on your intuitive *fast thinking* and then used faulty reasoning to justify it to me, even though you were under no pressure to answer me right away. You could have used the opportunity to systematically go through the pros and cons of turning over each card one by one, but instead you stuck with your original intuition and defended the cards you'd initially selected, hoping that I would be convinced.

Moses: I see your point.

Socrates: Now can you guess what might have been the original function for which reasoning via *slow thinking* evolved?

Moses: To convince other people that you are right, even when you're not?

Socrates: There you go! Think of it this way. If reasoning had originally evolved to confer a survival advantage by improving individual decision-making, then evolution would surely have selected for individuals with strong reasoning skills without confirmation bias. But that's not what tests like the Wason selection task show.

Moses: So you're claiming that reasoning originally evolved to win arguments, not to get at the truth? How does that make any sense?

Socrates: It makes perfect sense from the standpoint of natural selection. I'm not denying that an individual with superior reasoning skills doesn't have a competitive advantage. But if that individual indiscriminately shares valuable information achieved through their superior reasoning with less rational individuals, they are giving away their competitive advantage. Since natural selection rewards competitive advantages, natural selection would favor an individual with superior reasoning skills who doesn't share the information over one who does.

Moses: Even if it makes sense from the standpoint of natural selection, it's still seems very odd to me. You're making it sound like reasoning evolved to promote deception rather than truth! Why would natural selection reward that?

Socrates: Hugo and Dan[98] have called it the Argumentative Theory of Reasoning. Their reasoning goes like this: from an evolutionary perspective, it's clearly an advantage for social animals like humans to be able to come up with arguments to convince other members of the community to do what benefits them personally, whether or not the other members also benefit. That's a competitive advantage that natural selection can reward. Evolution doesn't really care whether your ability to persuade others is based on honest reasoning or clever deception, as long as the outcome favors your own self-interest over someone else's. Ergo, confirmation bias.

Moses: It's an interesting argument to account for confirmation bias. But it doesn't really explain why people are bad at reasoning. They should at least be good at biased reasoning, i.e. coming up with the best arguments to support their position, in order to get others to go along with them. But if most people get the simple Wason test wrong, like I did, then they aren't even very good at biased reasoning.

Socrates: Hugo and Dan [99] make an interesting argument in that regard.

Moses: Which is?

Socrates: It takes a lot of mental energy to methodically analyze all the best arguments justifying a decision. But since all you really need is one argument that satisfies your opponent, it's more efficient to try the first reason that comes to mind, whether it's good or bad. If your opponent is convinced, then the contest is over. If not, then you need to spend additional mental energy to come up with a more convincing reason. In the end, it's more efficient to use your mental energy incrementally, to try the first argument that comes to mind to see if it convinces your opponent, rather than wasting time and mental energy searching for all of the best possible arguments.

Moses: But if a person just throws out the first superficial reason that they think of, how likely is that to convince someone else?

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[98] **Hugo Mercier** and **Daniel Sperber.** Why do humans reason? Arguments for an argumentative theory. *Behav Brain Sci*. 2011;34:57-74; discussion 74-111; and *The Enigma of Reason.* Harvard University Press, 2017.

Socrates: That's what distinguishes a good arguer from a bad arguer. Good arguers are inherently better at coming up with convincing reasons from the start. In fact, good arguers are also skilled at anticipating counterarguments from their opponents, so that they are prepared to rebut them. Just like chess, it's best to think several moves ahead. I call it *second level thinking*, anticipating beyond the first level of *fast* and *slow thinking.* Make sense?

Moses: I suppose. But I still have a problem. If *slow thinking* is so fraught with faulty reasoning and confirmation bias, why is it any better than *fast thinking* alone? In other words, if all decisions are ultimately based on intuitive *fast thinking* anyway, why does *slow thinking* based on reason confer any advantage to humans over other animals?

Socrates: Because humans are social animals.

Moses: So what? Apes and monkeys and many other species are also social.

Socrates: But none of those other species have complex language. They only way that they can convince other individuals to do what they want is by physical coercion or deception. To convince by argument, you need complex language.

Moses: Even so, if all decisions are made intuitively using *fast-thinking*, why is convincing others using biased arguments any better than brute force?

Socrates: That's the beauty of it.

Moses: What do you mean?

Socrates: When decisions are made by physical coercion, the strongest individual invariably wins. But arguing with language is different.

Moses: How so?

Socrates: Imagine you have a group of humans facing some issue that requires a decision. Someone offers his or her opinion for the group to consider. Using the *fast thinking* mode, some members intuitively may agree and others may disagree. The proponents then use the *slow thinking* mode to come up with good arguments in favor of the proposed decision. However, because of their confirmation bias, they can only produce weak counterarguments. The opponents, on the other hand, have the opposite confirmation bias – they can come up with good counterarguments, but only weak arguments in favor of the proposed decision.

Moses: Ah, now I get it! That means that even though as individuals, humans can only come up biased reasons supporting their own view, the group as a whole ends up identifying both good arguments and good counterarguments.

Socrates: Exactly - the confirmation biases of the proponents and opponents are in opposite directions and cancel each other out!

Moses: And so wisdom emerges from bias. Beautiful! Competing but complimentary opposites – Ying and Yang once again.

Socrates: Impressive, isn't it? It's almost like two wrongs making a right.

Moses: Fascinating. Of course, for it to work, the members of the group have to be flexible enough to reach a consensus. Only if the members of the group are willing to consider both pros and cons, and change their minds depending on the most compelling set of arguments, will the most well-reasoned decision prevail.

Socrates: In fact, that's exactly what happens with the Wason selection task. If, instead of testing isolated individuals, you ask a group to solve the problem collectively, once one member of the group sees the correct answer and explains it to the others, everyone accepts it, just like you accepted my explanation. Since one out of ten usually sees the correct answer to the Wason four card selection task, a group of 10 people working collectively will usually get the correct answer, even though individually, nine out of ten will get it wrong.

Moses: So it really does work! Even though the individual reasoning is flawed by confirmation bias, collective reasoning logically arrives at the best decision. Like you said, two wrongs making a right!

Socrates: It's been called the Wisdom of Crowds. James [100] wrote a nice book on the subject, summarizing how under the right conditions crowds can often outperform individuals. One of my favorite examples is the story about Sir Francis, the renowned British statistician and geneticist [101].

Moses: Tell me about it.

Socrates: In 1906, while vacationing in the English countryside, he came upon a country fair sponsoring a contest to guess the weight of an ox. Being an aristocrat with a generally low opinion of common folks' intelligence, he predicted that the range of guesses would be wildly disparate. To prove his point, he asked the person in charge if he could have the tickets with the guesses on them after the contest was over. As expected, the 800 or so individual guesses were all over the map, ranging from way over to way under the true weight of the ox. However, when he calculated the average, he was astounded to discover that it fell within a pound of the ox's true weight.

Moses: Maybe that was just a lucky coincidence.

Socrates: You might think so, but it's been replicated many times – there's even a TED talk demonstration in which an ox was led onto the stage in front of a live audience.[102] And it's not the only example where crowds spookily outperform individuals. Like outfitting the seats of an auditorium with joy sticks and having the audience try to land an airplane on a flight simulator program. When inexperienced individuals try to land the plane by themselves, they crash every time because they overreact trying to adjust

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[100] **James Surowiecki**, *The Wisdom of Crowds: Why the Many Are Smarter than the Few and How Collective Wisdom Shapes Business, Economies, Societies, and Nations*. Random House, 2004. Surowiecki asserts that when the decision-making environment is not set up to accept the crowd, the benefits of individual judgments and private information are lost and the crowd can only do as well as its smartest member, rather than perform better.
[101] **Sir Francis Galton** (1822-1911), a half-cousin of Darwin who coined the terms "eugenics" and "nature versus nurture"
[102] **Lior Zoref:** https://www.youtube.com/watch?v=din2UVvRnGU

the flight path. But when the whole audience tries collectively, they are successful within a few tries, because the overreactors cancel out the underreactors. Just like an argument in which the opposite confirmation biases cancel each other out. That's the Wisdom of Crowds.

Moses: Fascinating, I have to admit. One small problem, though, especially with the flying example.

Socrates: What's that?

Moses: An expert pilot would have landed the plane without crashing on the first try. Which brings me to the question, would you board an airplane that the passengers were going to fly collectively in place of a trained pilot? Or suppose that you needed heart surgery. Would you let a crowd of laypersons operate on you instead of a trained heart surgeon?

Socrates: A valid point, Moses. I'm not suggesting that we dispense with airplane pilots or heart surgeons. In specific areas of expertise, highly trained experts will of course outperform a crowd of non-experts. But let me ask you this - how does an expert became an expert?

Moses: Like you said, they trained extensively in their area of expertise.

Socrates: Exactly. The pilot and heart surgeon each apply a narrow set of highly practiced technical knowledge and skills to a discrete problem whose solution has already been worked out. But they weren't born with that information. They studied the collective wisdom of generations of scientists, engineers and physicians who worked out of all those details. So where did all that came from?

Moses: What does that have to do with the Wisdom of Crowds? All of those scientists, engineers and physicians who developed the prerequisite bodies of knowledge needed to train a pilot or heart surgeon were all highly specialized experts in their disciplines. They were hardly crowds of lay persons.

Socrates: Doesn't that depend on how far back you go? Originally, there were no experts in either flying planes or performing heart surgery – those are very recent developments. In fact, originally, there were no scientists, engineers or physicians. Your ancestors started as simple nomadic hunter-gatherers. Their only expertise was in hunting and gathering.

Moses: Sure, but what's your point?

Socrates: My point is that Wisdom of Crowds doesn't just apply to a group of people trying to solve a problem in the here and now. Language, especially written language, allows the Wisdom of Crowds to be accumulated over successive generations so that each generation doesn't have to reinvent the wheel. In fact, the body of scientific knowledge is one of the greatest examples of the Wisdom of Crowds that humans have ever achieved. Think about it. What's required for a scientific discovery to be accepted into the pantheon of science?

Moses: I'd say that the discovery has to be based on sound reasoning validated by well-designed experiments.

Socrates: And who decides whether that reasoning validated by experiments is sufficiently sound? Is it the individual scientist making the discovery? Would that really be wise if scientists, like other humans, use *fast thinking* first and *slow thinking* second? Wouldn't the conclusions likely be contaminated by their confirmation bias?

Moses: Maybe scientists are better than nonscientists at reasoning logically without confirmation bias, since they have to support their ideas with experimental results, not just intuitions. That's how they've been trained, after all.

Socrates: Even so, how can you know that there wasn't serious confirmation bias in the way they went about designing the experiments to test their ideas? And there's another aspect of confirmation bias that's troublesome for scientists especially.

Moses: What's that?

Socrates: The evidence from human psychology experiments shows during *slow thinking,* people are generally much better at recognizing evidence that validates their *fast thinking* intuition than at recognizing evidence that falsifies it. Take the Wason four card selection task, for example (Figure 15-1). Most people pick the *E* card, which can validate or falsify the Rule. But they usually miss the *7* card, which can only falsify the Rule.

Moses: Okay, but why is that important?

Socrates: Because in science, falsification carries more weight than validation. Experiments that validate a theory are confirmatory, but do not prove that the theory applies generally under all possible conditions. Experiments that falsify a theory, on the other hand, prove unequivocally that the theory isn't generally true.

Moses: I see.

Socrates: And I remind you that, like most people, you picked the validating *E* card, but missed the falsifying *7* card, despite your extensive training and experience as a scientist. So if I want to be brutally honest, why should I trust the science that you've produced?

Moses: May I defend myself?

Socrates: Of course, please do.

Moses: First, you're right about the Wason test - I should have thought it through more carefully before answering. I guess I just wanted to impress you by coming up with an answer quickly, although why I should care about impressing a sea lion who has just insulted me, I have no idea. Second, as a scientist, I don't just throw out ideas and automatically have them accepted by the scientific community. There's a whole process involved in getting my ideas published in a scientific journal, much less accepted into the 'pantheon of science'. After my team and I formulate a hypothesis, design and perform experiments to test it, and write up the findings, we submit our manuscript to a journal, whose editor sends it to reviewers who are recognized experts in my field. They evaluate the paper to see if they find the findings and interpretation convincing. The journal then sends the paper back to us with the reviewers' critiques, to which we respond and revise accordingly. It's not until the reviewers and editor are both satisfied that the revised paper is accepted for publication. That's how the process works in modern science – nothing important gets published without first being vetted by peer review.

Socrates: Well-done, Moses! You've just eloquently described how science formally uses the Wisdom of Crowds to neutralize confirmation bias. The scientific team are the proponents who present their best arguments supporting their interpretation of the data, and the peer reviewers are the opponents whose explicit job is to identify weaknesses, counterarguments and falsifying observations against your interpretation. They argue back and forth, with the editor serving as the referee who ultimately decides, based on both the arguments and counterarguments, whether the paper deserves to be published.

Moses: It doesn't apply only to modern science. The consensus of the scientific community has always been required for a scientist's discoveries to be accepted and incorporated into the pantheon of science, even before formal peer review systems were adopted.

Socrates: Precisely my point. The pantheon of science is effectively a cumulative Wisdom of Crowds. That's exactly what Sir Isaac meant when he said:

> "If I have seen further, it is by standing on the shoulders of giants." [103]

Sir Isaac recognized that he couldn't have come up with his Laws of Motion completely on his own, without the accumulated Wisdom of Crowds passed down by his many predecessors. And even Sir Isaac had to argue vigorously with his scientific peers before he was able to convince them. When Gottfried, who was smart enough to independently invent calculus at the same time as Sir Isaac, first heard about Isaac's idea of gravity as an invisible force that attracts objects to each other, he said:

> "I say it cannot be done without magic."[104]

Eventually, though, scientists now accept gravity as a matter of fact.

Moses: Reminds me of that quote you mentioned before:

> "All truth passes through three stages. First, it is ridiculed. Second, it is violently opposed. Third, it is accepted as having been self-evident all along."

Socrates: Ah yes, Arthur's [105] famous quote.

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[103] The metaphor of dwarfs standing on the shoulders of giants expresses the meaning of "discovering truth by building on previous discoveries" has been traced to the 20th 20th twelfth century, attributed to Bernard of Chartres, but its most familiar expression in English is by Isaac Newton in 1675.
[104] **Gottfried Wilhelm von Leibnitz** (1646-1716)

Moses: And I guess it was the same for Albert, two hundred years later. He couldn't have formulated special and general relativity as tenets of modern physics without the contributions of Sir Isaac and many others to classical physics before him.

Socrates: And his ideas also were hotly debated before they reached Arthur's Third Stage of Truth.

Moses: I suppose it's understandable. When a scientist has a novel theory that challenges the currently accepted paradigm, he and she is judged by scientific peers who've often spent their careers validating that currently accepted paradigm. For them to admit that they were wrong is a hard pill to swallow.

Socrates: There's another quote that you'll like. This one is from Max [106]:

> "A new scientific theory does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die and a new generation grows up that is familiar with it."

Moses: Also a good one!

Socrates: I thought you'd appreciate it.

Moses: There's one thing still bothers me about the Wisdom of Crowds concept, at least as far as science is concerned. In the examples you've just described, the peer reviewers are all experts in the same discipline as the scientist proposing the new idea. That means that whether or not the new theory is accepted depends on the Wisdom of Crowds of Experts, rather than the Wisdom of Crowds of Non-Experts. Not only that, we already agreed that for flying a plane or performing heart surgery, you're better off with one well-trained pilot or heart surgeon than a crowd of none-experts. So if we're going to rank wisdom, I'd put it in order of the Wisdom of Crowds of Experts first, the Wisdom of a Lone Expert next, and the Wisdom of Crowds of Non-Experts last.

Socrates: When the experts all agree on the best overall solution, I have no objection to your ranking system. But what if the experts don't agree? If each expert's reasoning is contaminated by his or her own confirmation bias, then who are the non-expert laypersons supposed to believe? As Bertrand [107] so nicely put it:

> "The scepticism that I advocate amounts only to this: (1) that when the experts are agreed, the opposite opinion cannot be held to be certain; (2) that when they are not agreed, no opinion can be regarded as certain by a non-expert; and (3) that when they all hold that no sufficient grounds for a positive opinion exist, the ordinary man would do well to suspend his judgment."

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[105] **Arthur Schopenhauer** (1788-1860)
[106] **Max Planck** (1858-1947), from *Scientific autobiography and other papers*
[107] **Bertrand Russell** (1872 –1970), from his essay "On the Value of Scepticism" in his 1958 book *The Will to Doubt*.

Moses: Doesn't that just put us back at square one? It's one thing to rely on the experts when the solution to a problem is known, like flying a plane or performing heart surgery. But for entirely new problems whose solutions are unknown, who is a layperson supposed to believe when the experts disagree? If we just go with our intuitive gut feelings, then how does that give us any advantage over animals who are incapable of reasoning?

Socrates: Here's how Jonathan[108] explains it:

> "Gut feelings are sometimes better guides than reasoning for making consumer choices and interpersonal judgments, but they are often disastrous as a basis for public policy, science, and law. Rather, what I'm saying is that we must be wary of any individual's ability to reason. We should see each individual as being limited, like a neuron. A neuron is really good at one thing: summing up the stimulation coming into its dendrites to "decide" whether to fire a pulse along its axon. A neuron by itself isn't very smart. But if you put neurons together in the right way you get a brain; you get an emergent system that is much smarter and more flexible than a single neuron. In the same way, each individual reasoner is really good at one thing: finding evidence to support the position he or she already holds, usually for intuitive reasons. We should not expect individuals to produce good, open-minded, truth-seeking reasoning, particularly when self-interest or reputational concerns are in play. But if you put individuals together in the right way, such that some individuals can use their reasoning powers to disconfirm the claims of others, and all individuals feel some common bond or shared fate that allows them to interact civilly, you can create a group that ends up producing good reasoning as an emergent property of the social system. This is why it's so important to have intellectual and ideological diversity within any group or institution whose goal is to find truth (such as an intelligence agency or a community of scientists) or to produce good public policy (such as a legislature or advisory board)."

Moses: I like the neuron analogy! Just like the Wisdom of the Brain emerges from stimulatory and inhibitory neurons wired together interactively, the Wisdom of Crowds arises from biased proponents and opponents wired together interactively. And it also fits with neural networks used in machine learning. Simple unintelligent nodes weighted and biased to detect increasingly complex patterns from layer to layer. None of them alone can identify the image until the full picture emerges at the output layer.

Socrates: In other words, the crowd's decision-making process is a bottom-up, rather than a top-down, process (Figure 10-1). Only when everyone in the crowd participates actively are the confirmation biases optimally neutralized so that the final consensus decision has been thoroughly vetted based on the unbiased reasoning.

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[108] **Jonathan Haidt**, *The Righteous Mind: Why Good People Are Divided by Politics and Religion.* Vintage Books, 2012. p. 105-106 of the Kindle Edition.

Moses: Still, the key phrase in the neuron analogy is "But if you put neurons together in the right way you get a brain; you get an emergent system that is much smarter and more flexible than a single neuron." The same is true for crowds – they have to be put together in the right way. Not all crowds are wise. They can also be unruly and degenerate into hysterical mobs that make rash, poorly thought-out decisions.

Socrates: Very true. Crowds can certainly get out of hand, especially if they've been stirred up by a demagogue spouting emotionally-charged rhetoric. Even calm and collected crowds can make poor decisions if the members all think alike. Then they just end up reinforcing each other's confirmation biases. Instead of the Wisdom of Crowds, you get Groupthink.

Moses: You mean like the Bay of Pigs invasion during the Kennedy administration? Isn't that a classic example of Groupthink?

Socrates: Exactly, as was the escalation of the Vietnam War by the Johnson Administration. In both of those cases, the ideological biases of the decision-making politicians and their advisors were too similar for them to think through the potential counterarguments. To avoid Groupthink, the crowd has to include individuals with diverse viewpoints who are flexible enough to weigh the pros and cons and then mold a consensus decision that the majority can support. That's when the confirmation biases of the proponents generating solid arguments and opponents generating solid counterarguments allow for an informed well-reasoned decision.

Moses: Is diversity the main criterion, then?

Socrates: It's one of them. James [109] breaks it down into four criteria.

Moses: What are they?

Socrates: The first criterion is *decentralization:* individuals have to draw on specialized local knowledge about the problem that is not uniformly appreciated. That helps to come up with a diverse range of proposed solutions to address the problem. Next is *diversity* of opinion: individuals have to be willing to express diverse opinions without fear or intimidation by the crowd. Third is *independence:* individuals have to stick to their own reasoning and not be too easily swayed by others, so that both good arguments and good counterarguments can be flushed out for each option using the *slow thinking* mode. The last is *aggregation:* there has to be a mechanism to integrate and synthesize the various opinions of individuals into a collective decision. If all four criteria are met, then consensus decisions by a crowd do very well. If not, the benefits of individual judgments and private information are lost and the crowd can only do as well as its most persuasive member.

Moses: I'm still struggling a bit with the *diversity* criterion. It doesn't seem to me that more diversity is always better. For example, I can see how the heart surgeon might be able to perform a more successful operation if he or she were advised by other heart

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[109] **James Surowiecki**, *The Wisdom of Crowds: Why the Many Are Smarter than the Few and How Collective Wisdom Shapes Business, Economies, Societies, and Nations*. Random House, 2004.

specialists in planning the surgery, especially if it was a very complex surgical procedure. But if the advisors were plumbers, lawyers, economists and politicians, they wouldn't be of any help at all. Too much diversity is counterproductive, don't you think?

Socrates: Here's how I look at it. Remember why we said that other animals can't exhibit crowd wisdom?

Moses: Sure. You pointed out that without complex language, other animals have no way to debate whether one approach is better than another. The only option is for the dominant alpha to make the decision unilaterally.

Socrates: Exactly. And what if you had a crowd of humans who each spoke a different language?

Moses: If no one could understand each other, then they couldn't debate the pros and cons either.

Socrates: Precisely. The point is that the individuals in the crowd have to speak a common language. In the case of heart surgery, even though plumbers, lawyers, economists and politicians may all speak fluent English, they are functionally illiterate in the technical language of heart surgery, so they wouldn't be of much help to the heart surgeon. It really falls under the *decentralization* criterion – that individuals have to draw on *specialized local knowledge* about the problem that is not uniformly appreciated. The plumbers, lawyers, economists and politicians don't have any specialized local knowledge about heart surgery, but other cardiovascular specialists, like cardiologists, anesthesiologists and radiologists, certainly do. Same for a trained pilot – advice from a crowd of non-pilots who all speak English but have no technical knowledge about aviation are pretty useless in helping the pilot to land the airplane safely.

Moses: I guess that makes sense. One final question, then.

Socrates: Shoot.

Moses: The *aggregation* criterion – you said that synthesizing the individual opinions into a consensus decision requires that proponents and opponents both be flexible in weighing arguments and counterarguments, and be willing to change their minds depending on whether the pros or cons are more convincing. Then they all need to have their own say in the final decision. That sounds to me a lot like democracy.

Socrates: Certainly. Everyone has to be able to speak their mind openly and have an equal vote in the final decision.

Moses: But as I recall, democracy wasn't invented until the ancient Greeks, and only lasted on a few hundred years in Athens. For thousands of years before and after that, the big decisions in human societies have been made by authoritarian leaders, such as big men, chiefs, pharaohs, patriarchs, monarchs, emperors, etc. It really wasn't until the late eighteenth century that democratic forms of government reappeared and gradually became more common. If that's the case, then the Wisdom of Crowds phenomenon should not really have had much of an impact on the development of human societies up to the present era, correct? Instead, for most of human history, the confirmation biases of the powerful authoritarian leaders would have dominated decision-making without taking advantage of the Wisdom of Crowds.

Socrates: Perhaps you should brush up on your anthropology, Moses! You are right that authoritarian leaders have dominated most societies over the past 5,000 or so years of *recorded* human history – that is, since written language was invented. But that's only a small fraction of the time that humans have existed on earth. The earliest members of the genus *Homo* appeared several million years ago, and anatomically modern humans have been around for at least 55,000 years [110]. Sometime in that pre-history period is when complex language, *slow thinking* and reasoning first evolved, during the so-called Cognitive Revolution. So the question you should be asking is whether those early human societies were dominated by authoritarian leaders.

Moses: Are you suggesting that they were not?

Socrates: Like I said, you need to brush up on your anthropology!

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[110] **David Reich**. *Who are We and How We Got Here: Ancient DNA and the Science of the Human Past.* Random House, 2018.

CHAPTER 16: From Grooming to Gossip

Moses: I admit that anthropology is not my field. What am I missing?

Socrates: Here are the highlights [111]. According to genetic analysis, humans and your chimpanzee/bonobo great ape cousins diverged from a common ancestor sometime between four to eight million years ago (Figure 16-1). In the fossil record, the human lineage begins with *Australopithecus* about four million years ago. The first members of the genus *Homo, H. habilis* and/or *H. erectus,* appeared 1.9-2.6 million years ago, and both used stone tools. Double-edged stone axes date to 1.75 million years ago and were probably used to strip meat from bones rather than as weapons, since they were less than eight inches long. The oldest known *bone fide* weapons are spearheads from a *H. heidelbergensis* archaeological site in the Kalahari Desert about half a million years old [112]. Anatomically modern *H. sapiens* appeared in Africa about 250,000-350,000 years ago, and migrated globally about 55,000 years ago. In those days, humans lived their lives as simple foragers, small bands of nomadic hunter-gatherers who subsisted off whatever the land provided. It wasn't until about ten thousand years ago that humans began to domesticate livestock and grow crops. That was the Agricultural Revolution, eventually followed by the Industrial Revolution about two hundred fifty

Nature's Timetable	
Birth of the Universe	13.8 billion years ago
Formation of planet Earth	4.5 billion year ago
First lifeforms	3.5 billion years ago
First primates	55 million years ago
Chimpanzee (*Panina*) and human (*Australopithicus)* lineages split from a common ancestor	4-8 million years ago
First members of genus *Homo (H. habilis* and *H. erectus)* using stone tools	1.9-2.6 million years ago
First weapons (*H. heidelbergensis)*	500,000 years ago
Origin of anatomically modern humans (*H. sapiens)* in Africa	250,000-350,000 years ago
Global migration of anatomically modern humans	55,000-70,000 years ago
Agricultural Revolution	10,000 years ago
Industrial Revolution	250 years ago
Information Revolution	40 years ago

Figure 16-1. Nature's Timetable

[111] See https://en.wikipedia.org/wiki/Human_evolution#Evidence_from_molecular_biology
[112] See http://news.nationalgeographic.com/news/2012/11/121116-stone-spear-tips-Science-human-neanderthal-hunting/ AND http://news.nationalgeographic.com/news/2007/10/071018-neandertal-gene.html

years ago, and the Information Revolution in the late twentieth century. That, in a nutshell, is your species' history on earth so far.

Moses: And when during this four to eight million year journey do you think that we first became capable of *slow thinking* and reasoning?

Socrates: Hard to say exactly.

Moses: It must have been fairly early on.

Socrates: Why?

Moses: How else can you explain our evolutionary success except as brains over brawn? As you pointed out before, pretty much any animal close to our own size, including our closest cousin the chimpanzee, is physically much stronger, more agile and more ferocious than we are. Unarmed, we wouldn't stand a chance in one-on-one combat. The obvious explanation is that we were able to outsmart other animals. Instead of having to rely solely on intuition and *fast thinking* like other animals, we could use *slow thinking* and reasoning to develop more and more sophisticated tools, including weapons. And once we had weapons, no other predators could compete with us! That's the secret of our success.

Socrates: Whoa, slow down! No doubt that weapons eventually gave you a big advantage over other predators, but your ancestors started walking upright on two legs and using stone tools several million years ago. They were already accomplished at surviving, including defending themselves from large predators, well before any *bona fide* weapons appeared on the scene as far as we know. Remember, the oldest weapon in the archaeological records is only a half million years old.

Moses: Perhaps, but even if weapons didn't come till later, it was still the investment in brains over brawn during the Cognitive Revolution that gave humans their advantage of the rest of the animal kingdom.

Socrates: Hard to disagree with that.

Moses: Then how did it start?

Socrates: What do you mean?

Moses: Reasoning didn't just appear suddenly out of the blue from some random mutation creating a gene for reasoning. There must have been hundreds or thousands of gene mutations that had to occur gradually over time for our ancestors to evolve a brain capable of reasoning.

Socrates: Ah yes, another one of the classic paradoxes in the evolutionary theory. But unlike the *Robustness versus Adaptability Paradox*, it's one that hasn't yet been resolved to everyone's satisfaction.

Moses: What paradox are you referring to?

Socrates: I call it the *Origin of Complex Features Paradox*. Basically, a variation of the "Which comes first, the chicken and the egg?" conundrum. According to the theory of evolution, genetic mutations become enriched in a population only when they confer a survival advantage, or are located on a chromosome close to a gene that does. But if hundreds or thousands of gene mutations had to occur for your ancestors' brains to become capable of reasoning, and their brains therefore didn't gain the survival advantage of reasoning until the last of those critical mutations occurred, then you have a paradox. What drove all of those genes to become enriched in the population before the last mutation occurred to confer the survival advantage of reasoning?

Moses: That's the paradox that the Intelligent Design crowd is so fond of. Like how birds evolved wings. They argue that countless generations of flightless birds would have to lug around rudimentary wings that were useless for flying before flying actually became possible. If those rudimentary wings were useless, they should be eliminated by natural selection before the bird ever had a chance to get off the ground, much less soar through the skies.

Socrates: Fortunately, in the case of birds' wings, it's not an issue.

Moses: Why not?

Socrates: Because birds inherited their wings from flying dinosaurs.

Moses: Okay, I set myself up for that one. But that only defers the issue to the dinosaurs. How did dinosaurs manage to survive lugging around rudimentary wings before they could use them to fly?

Socrates: The usual explanation is that rudimentary wings evolved to serve a different useful purpose, and only later were adapted to flying. Evolutionary biologists call it *exaptation* when a trait that originally evolved to serve one function is subsequently is co-opted to serve another function. In the case of dinosaurs, one hypothesis is that rudimentary wings may have acted as stabilizers allowing small dinosaurs to run faster on two legs without losing their balance when fleeing from predators. Maybe wings then further evolved to allow tree-living dinosaurs to glide from tree-to-tree, like flying squirrels today. Then in the final stage, the wings were adapted to flight as the natural extension of gliding. In the same vein, feathers are also considered to be an example of exaptation that evolved first for temperature regulation, and only later were co-opted for flying.

Moses: A nice story, but how can you prove it?

Socrates: That's the problem. When hundreds or thousands of gene mutations are involved in forming all of the new specialized tissues, muscles, bone structures, neuronal innervation, blood supply, and so forth required for wings to become functional, it's hard to visualize how each one individually contributed some specific survival advantage unrelated to flying. Not only that, but since the fossil record is incomplete, there's a lot of guesswork about the missing links between the dinosaurs that couldn't fly and those that could.

Moses: Then do you buy the Intelligent Design argument?

Socrates: No, but I understand its appeal. If you already believe in God, then it's intuitively much easier to imagine complex structures being created from the top down by an all-powerful Creator, just like an engineer would design the wings for an airplane. But complex structures can also arise from the bottom up – for example, the self-organizing patterns and biological clocks driven by feedback loops, or machine learning algorithms that train themselves to perform sophisticated tasks by minimizing a cost function. Feedback is great at empirically learning new things.

Moses: You mean like the neural network algorithm for recognizing hand-written digits?

Socrates: Exactly. Even for that shallow neural network with only one hidden layer (Figure 11-3 & 11-4), over a hundred thousand initial weights and biases had to be adjusted (mutated) to train the network to recognize the hand-written digits. Random guesses got us nowhere, but when the training was automated by an algorithm using feedback in the form of gradient descent to minimize a cost function, it only took a few iterations (generations) to reduce the error rate from 90% to 7% (Figure 11-6).

Moses: I have to admit, it was very impressive how quickly the neural network algorithm learned to adjust all of those parameters!

Socrates: Impressive and also somewhat mysterious. Because of the way in which everything affects everything else inside the hidden layers linking the input layer to the output layer, it was not really possible to decipher logically why those particular final weights and biases after the training worked so much better than the initial randomly selected values. For the most part, the logic inside the black box was impenetrable.

Moses: I see where you're going. If genomic learning is conceptually similar to machine learning, with a black box of many hidden layers of networks linking the genotype to the phenotype (Figure 12-1), then the same indecipherability might arise.

Socrates: Exactly. To evolve wings that can fly or brains that can reason, the genomic learning algorithm is empirically adjusting large numbers of individual combinations of genetic variants over many generations to train new organs to function properly. And, like a machine learning algorithm, the black box of complex biological networks obscures the connections between the input layer of the genotype and the output layer of the phenotype in such a convoluted manner that it's impossible to discern the logical relationships between the two. All of the feedback between genetics and epigenetics obscures what's causal and what's reactive. Yet somehow, with genetic optimization as the cost function, the feedback process produces wings that can fly and brains that can reason.

Moses: It is mysterious, this black box issue. Do you think we'll ever be able to make sense of it?

Socrates: Possibly, if and when some future geniuses come up with the "black box calculus" that we talked about before. Until then, my guess is that you're going to have a hard time dissuading the doubters from supernatural explanations like Intelligent Design.

Moses: Definitely a worthy challenge for ReliEnce, don't you think?

Socrates: Indeed. Meanwhile, you'll have to rely on the exaptation explanation as your best shot. On the bright side, though, even if exaptation is hard to prove, it's fun to speculate about!

Moses: Then what about the ability to reason? If wings first evolved to improve balance while running and only later were co-opted for flying, then what could have caused our ancestors' brains to enlarge so that its greater cognitive power could be co-opted for *slow thinking* and reasoning?

Socrates: I'm sure that with a little *slow thinking* and abductive reasoning, we can come up with a hypothesis! Subject to our own confirmation bias, of course.

Moses: I suppose that's unavoidable.

Socrates: Naturally, but that wasn't why I mentioned it.

Moses: Why then did you mention it?

Socrates: More as a clue than a caveat.

Moses: A clue to how *slow thinking* and reasoning evolved?

Socrates: Remember the Argumentative Theory of Reasoning [113] - that as individuals, humans use *slow thinking* and reasoning mainly to persuade others to follow what they've already decided intuitively using *fast thinking*.

Moses: Sure, the confirmation bias problem – reasoning as window-dressing that doesn't improve decision-making. It may confer a survival advantage to the best arguers within the community, but not necessarily to the whole community in competing against outsiders.

Socrates: Exactly. Individual reasoning is not what gives human communities a survival advantage. What gives human communities a survival advantage is collective reasoning, assuming that the community meets the criteria for the Wisdom of Crowds phenomenon that we discussed earlier. That's the clue that I was talking about.

Moses: Sorry, but I still don't get it.

Socrates: The point is that collective reasoning requires more than just the ability to reason. It also requires the ability to form cohesive social groups meeting the Wisdom of Crowds criteria – decentralization, diversity, independence, and aggregation essential for wise collective decision-making.

Moses: Are you proposing that our ancestors' brains enlarged because of the need to develop more cohesive social groups, and that only later was the greater cognitive power exapted to *slow thinking* and reasoning?

Socrates: Precisely.

[113] **Hugo Mercier** and **Daniel Sperber**. *The Enigma of Reason.* Harvard University Press, 2017.

Moses: But chimpanzees evolved from the same common ancestor as us, and they live in cohesive social groups. Why didn't their brains enlarge the same way?

Socrates: Because when your common ancestors climbed down from the trees and started living on the ground, they faced different challenges than ones who remained aloft. It's more challenging to evade large predators when you can't just scamper up a tree. To live on the ground, well-coordinated groups are essential for survival. As Tamas and Robin[114] have explained it:

> "In primates, the principal selection factor favoring group-living is protection against predators, and continues to be so in humans, where predators are to be understood as being either conventional carnivores or conspecific raiders. However, solving that ecological problem requires that the individual animals can form and maintain a coordinated, cohesive social group. In such cases, the effectiveness of defense is provided by the size of the group, and the size of the group is simply a function of how well individuals can coordinate their behavior so as to remain together. The cost that is paid for doing so is minimal, because individuals are not explicitly involved in active defense—it is the simple presence of the group that deters predators and raiders, not the action of individual group members. More importantly, they are not engaged in exchanging any kind of commodity (including information), and therefore individual animals cannot face the prospect that others might contribute less than they do. As a result, the free rider problem that gives rise to the collective action paradox is not so intrusive: an individual cannot 'pay' more or less than anyone else for the benefit gained from defense—it simply joins the club or it does not, and it benefits accordingly (and may pay a heavier cost if it doesn't join by incurring a higher predation risk if it forages alone or in a smaller group). Taken together, these results imply that human sociality is less about dyadic exchange and more about achieving social coordination at the community level."

Moses: What do they mean by dyadic exchange?

Socrates: Dyads mean pairs. Other primates depend on grooming to maintain and reinforce social ties. It's a peaceful way to acknowledge rank in the community without resorting to physically violent challenges that entail a risk of serious injury or even death. But the downside is that grooming is limited to two individuals at a time. It's great for promoting social cohesion between pairs, but not well-suited for coordinating social activities at the broader level of the whole community. Your human ancestors needed a more efficient method for multiple members of the community to communicate with each other simultaneously.

Moses: Like language?

Socrates: Exactly. To be more specific, a particular aspect of language.

Moses: What's that?

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[114] **Tamas David-Barrett, Robin Dunbar**. Language as a coordination tool evolves slowly. *R Soc Open Sci*. 3:160259, 2016.

Socrates: Gossip. Your common ancestors who stayed in the trees and stuck with grooming evolved to become chimpanzees. The ones who relocated to the ground and replaced grooming with gossip to cement social ties evolved into humans.

Moses: But language isn't unique to humans. Chimpanzees use language. So do primates with even smaller brains, like Vervet monkeys. They use different sounds to indicate different predators like leopards, eagles or snakes. Even non-primate social animals have vocabularies to raise alarm, defend territory or attract mates. [115]

Socrates: It's true that many social animals use language, but they are simple languages consisting mostly of nouns. Only humans have evolved simple language into complex language capable of expressing abstract concepts. That's the key. To be able to gossip, for example, requires marking time and place as well as identifying specific individuals and commenting on their actions. Same for reasoning - you can't reason, either individually or collectively, without abstract concepts like those.

Moses: So because living on the ground required a more sophisticated form of social communication for coordinating community defenses, our human ancestors evolved simple language into complex language and let grooming fall by the wayside?

Socrates: Exactly. And as language evolved, natural selection favored larger brains with greater cognitive power that could process increasingly complex abstract thoughts, as well as alterations to other organs needed to facilitate language.

Moses: Like what other organs?

Socrates: The larynx, for example, where your vocal chords live. In case you haven't noticed, chimpanzees and other great apes have a pretty restricted vocal repertoire - shrieks and grunts mostly, with a limited ability to enunciate vowels. Just like you needed a larger brain to convert your thoughts into words, you needed to improve your vocal range in order to articulate those words.

Moses: What's different about the human larynx?

Socrates: Compared to the larynx of great apes and monkeys, it's positioned lower in the neck, below the epiglottis and soft palate[116]. That creates a pharyngeal cavity in addition to the buccal cavity formed by your cheeks, which allows humans to articulate a much wider range of sounds, especially vowels. The larynx in great apes and monkeys, by contrast, is above the epiglottis, so they have only the buccal cavity to modulate sounds. But the lower position of the larynx comes at a cost.

Moses: What's that?

Socrates: It prevents humans from breathing and swallowing at the same time, which increases their risk of choking.

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[115] **A. Kershenbaum** et al. Acoustic sequences in non-human animals: a tutorial review and prospectus. *Biol Rev Camb Philos Soc* 91(1): 13-52, 2016.
[116] **C. Buckley** and **J. Steele**. Evolutionary ecology of spoken language: co-evolutionary hypotheses are testable. *World Archaeol*. 34:26-46, 2002.

Moses: So a wider vocal range was worth a higher risk of choking?

Socrates: Apparently so.

Moses: How long ago did this happen?

Socrates: Unfortunately, no one really knows. Since the larynx is mostly made of cartilage, it isn't preserved in skeletal remains.

Moses: Even so, our human ancestors didn't just wake up one morning with an expanded vocabulary and complex language. It must have been a gradual process involving a wide range of gene mutations. What do you think started it off?

Socrates: No one knows for sure, but I have a pet theory.

Moses: What's that?

Socrates: You know how a rousing speech can whip a crowd into a frenzy?

Moses: Sure. Like a pep talk to a football team, or a political rally. However, those require complex language.

Socrates: True, but what else besides a rousing speech can do that? Here's a hint - think of celebrations.

Moses: Music and dancing?

Socrates: Very good, Moses, right on the beat! Singing, dancing, drumming are ubiquitous in all human societies, from hunter-gatherer bands to modern nation-states. But have you ever seen an ape, monkey, dog or cat tapping its paw or swaying rhythmically in time to music? Have any dancing bears, elephants or monkeys ever reminded you of Fred Astaire and Ginger Rogers? As it stands, you're one of very few species that has a sense of rhythm [117].

Moses: What about birds? Birdsongs are melodic, and birds also perform rhythmic mating dances [118]. The Australian lyrebird [119] even sings and dances at the same time. There are even birds that can dance to human music – I've seen a video of a cockatoo named Snowball who has better dances moves than most humans [120]!

Socrates: Which just goes to prove that singing and dancing evolved to serve social functions in other species as well, like mating rituals in birds.

Moses: And mating rituals in humans too.

Socrates: Definitely, but in humans, it goes well beyond mating rituals. Just think of all the additional ways humans use singing and dancing – preparation for warfare, hunts and competitions, praying, celebrating, soothing, grieving and so on. Rhythmic chanting, melodic singing, drumming and dancing are very effective at synchronizing the

[117] Earliest musical instruments: percussion 165,000 years old; flute 67,000 years ago; see https://www.smashinglists.com/10-earliest-known-musical-instruments/
[118] See https://www.mnn.com/earth-matters/animals/stories/10-bizarre-beautiful-bird-courtship-dances
[119] See https://www.youtube.com/watch?v=5Js9DTOoYEM
[120] See https://www.youtube.com/watch?v=N7IZmRnAo6s

emotional state of the whole community. And it's highly effective whether or not words are involved. Music creates a sense of unanimity that makes people feel part of something greater than themselves – it's much more powerful than grooming at emotionally galvanizing an entire community.

Moses: Everything you've said makes sense so far. Living on the ground required better coordinated social groups that were more cohesive, more cooperative and less individualistic than typical primate alpha hierarchy communities. Those adaptations favored larger brains with greater cognitive capacity capable of expanding simple language into a more effective method for social coordination than grooming. Likewise, the same evolutionary pressures selected for anatomical changes that expanded the human vocal range, both to evolve music and other rhythmic forms promoting social cohesion as well as to facilitate articulation of a growing vocabulary.

Socrates: Bravo, Moses, an excellent summary!

Moses: What happened from there, though? We still haven't really explained how the ability to formulate and articulate abstract concepts that distinguish simple language from complex language came about. Ultimately, that's the key to both gossip and reasoning.

Socrates: My guess is that the fusion of music with simple language gradually evolved into complex language. Group singing and dancing requires performers to synchronize their voices and positions – that is, to be able to mark time and place. Once you have a sense of marking time and place, then it's a short step to being able to communicate third party information [121].

Moses: Third-party information?

Socrates: It's a foundational aspect of complex language, and gossip in particular. Let me give you an example. With simple language, a primate can vocalize a distinct sound for "leopard" to warn every great ape within earshot of an imminent danger. But that's about all. Without complex language, that primate has no way to communicate to a third party who wasn't there at the time that "I saw a leopard yesterday by the river. We should avoid that spot." Collective strategic planning requires marking time and place as well as identifying third parties and commenting on their actions, i.e. transmitting third party information. It requires what psychologists call Theory of Mind.

Moses: What's that?

Socrates: The realization that other individuals can have beliefs about the world that differ from one's own.

Moses: And other animals don't have that capability?

Socrates: Even human children lack that capability before the age of four.

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[121] **A. Bissonnette, S Perry , L Barrett , JC Mitani, M. Flinn, S Gavrilets** and **FBM de Waal**. Coalitions in theory and reality: a review of pertinent variables and processes. *Behaviour*. 152:1-56, 2015; and **T. David Barrett** and **K.R. Dunbar**. Language as a coordination tool evolves slowly. *R Soc Open Sci*. 3:160259, 2016.

Moses: How can you tell?

Socrates: Because standard tests for Theory of Mind have been developed by psychologists.

Moses: Like what?

Socrates: False belief tests are a good example. In the 1980s, a popular version developed by child psychologists is called the Sally-Anne test. It goes like this. A child is shown two dolls named Sally and Anne, who have a basket and a box, respectively. The Sally doll also has a marble, which she places in her basket, and then leaves the room. While Sally is out of the room, Anne takes the marble from Sally's basket and puts it into her box. When Sally returns, the child is then asked where Sally look for the marble. It's obvious to you and me and most children over the age of four that Sally will look in her own basket, since she has no way of knowing that Anne moved the marble into her box when she was out of the room. That is, we have Theory of Mind that allows us to recognize that Sally can hold a false belief different from what we, in our own mind, know to be true.

Moses: What about a child under four?

Socrates: Under the age of four, most children will answer that Sally will look for the marble in Anne's box. They have not yet developed Theory of Mind and so can't yet comprehend that Sally could hold a false belief different from their own. Without Theory of Mind, it's hard to recognize that there's any need to transmit information to a third party, since in your mind, the third party already knows everything that you know. That's a big limitation for coordinating strategies like community defense that require collective action.

Moses: And no other primates except humans have Theory of Mind?

Socrates: There are examples that have been interpreted as such, but it's still controversial [122]. In baboons, for instance, there's an account of a juvenile tentatively approaching an adult baboon feeding at a patch of overturned turf [123]. Although the adult made no threat, the youngster suddenly screamed, attracting a higher-ranking adult to rush over. In response, the low-ranking adult retreated, leaving the site available for the juvenile. Some experts have argued that tactical deception like that, requiring the juvenile to anticipate how his scream will attract a dominant adult and cause a low-ranking adult to retreat, requires Theory of Mind. However, other experts argue that alternative explanations are possible. For example, the juvenile might have tried to encroach upon a feeding adult before, been attacked and screamed, thereby attracting a higher-ranking adult who then chased off the low-ranking adult left. If that scenario happened a few times so that the youngster made an association between his screaming and the feeding adult retreating, he might, without conscious deception requiring Theory of Mind, adopt that tactic repeatedly.

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[122] **C. M. Heyes**. Theory of mind in nonhuman primates. *Behav Brain Sci.* 21(1): 101-14, 1998.
[123] **A. Whiten** and **R. W. Byrne.** Tactical deception in primates. *Behav Brain Sci* 11: 233-273, 1988.

Moses: You mean like Pavlov's dogs beginning to salivate when the bell rings, once they've been trained to associate the bell ringing with delivery of food.

Socrates: Exactly.

Moses: I guess that it's easy to see how complex language facilitates Theory of Mind. If someone can tell you directly what they are thinking, it doesn't take long to realize that they often hold different beliefs from your own!

Socrates: And conversely, if someone can't explain to you what they are thinking, it's not so easy to develop Theory of Mind, even for adult humans. For instance, congenitally deaf adults who were never taught to communicate by signing or lip reading as children do poorly on false belief tests like the Sally-Anne task [124], as do many autistic children.

Moses: It seems to me that collective reasoning definitely requires Theory of Mind. How could you ever reach a consensus if members of a group can't imagine others holding different opinions than their own?

Socrates: I agree.

Moses: Anything else you'd care to add to our hypothesis that *slow thinking* and reasoning evolved through exaptation?

Socrates: Just one more thing.

Moses: What's that?

Socrates: There's another aspect of reasoning that owes a lot to music and dancing, although it didn't really blossom until relatively late in human evolution, after the Agricultural Revolution.

Moses: What's that?

Socrates: Mathematics.

Moses: I don't quite follow you.

Socrates: Music is about rhythm, counting, intervals and ratios. Musicians count off the tempo when they start to play. Songs consists of measures of musical notes, and notes are divided into intervals such as whole notes, half notes, quarter notes, eighth notes, etc. The notes of the musical scale correspond to specific ratios of the lengths of vibrating strings [125] . If I were to guess, I'd say that music in the form of singing, dancing and drumming is what gave your human ancestors an intuitive feel for numbers, counting, intervals and ratios. Eventually, that intuition blossomed into the language of mathematics and mathematical reasoning.

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[124] **F. Lecciso1, A. Levante, F. Baruffaldi and S. Petrocchi**. Theory of Mind in deaf adults. *Cogent Psychology* 3: 1264127, 2016.

[125] In the **Pythagorean major scale**, the 8 notes C, D, E, F, G, A, B, C correspond to length ratios of 2:1, 15:8, 5:3, 3:2, 4:3, 5:4, 9:8, 1:1. See https://pages.mtu.edu/~suits/pythagorean.html

Moses: Ah, finally an explanation for why chimpanzees can't do math - no sense of rhythm! I've always wondered about that one.

Socrates: I'm glad that you find my conjecture amusing. I admit, it's just a personal speculation.

Moses: But an intriguing one nevertheless. Overall, I actually think your ideas about the evolution of *slow thinking* and reasoning make a lot of sense.

Socrates: Good. It's great to know that our confirmation biases are generally aligned!

Moses: Our confirmation biases? That's not very reassuring.

Socrates: What do you expect? It's really no more than an initial hypothesis that we've formulated using our combined efforts at adjunctive reasoning. It still has to be subjected to a decentralized, diverse, independent, aggregated critique by the broader human community at large, spanning at least a few card-carrying evolutionary anthropologists, machine learning experts and Intelligent Design advocates. That's how collective reasoning and the Wisdom of Crowds works. And it's what Reli-Ence should demand.

Moses: What, everyone ganging up on us to shoot down a speculative hypothesis? That doesn't sound very appealing.

Socrates: What are you afraid of? After all, you have a talking sea lion to back you up! Besides, they don't get to just shoot down our hypothesis – they have to defend their own hypothesis, whether it's based on exaptation, black box impenetrability, Intelligent Design or some other idea.

Moses: And you really expect such a diverse group to come to a consensus?

Socrates: No, of course not. But that's okay, as long as they agree to disagree and treat each other's opinions respectfully, like we just did. The point is to get people listening to each other instead of shouting at each other! That's the only way ReliEnce will ever make any real headway!

CHAPTER 17: Gossip and the Egalitarian Transition

Moses: If we are going to defend our hypothesis to the world at large, it has to be as airtight as possible, don't you think? Perhaps we should review it again and try to anticipate criticisms that might come up.

Socrates: I couldn't agree more. Why don't you summarize the main points, and see if we can spot any major weaknesses.

Moses: Sure. Here's what we came up with. When my human ancestors left the safety of the trees, surviving on the ground required a higher level cooperation between members of the community in order to defend against large predators and rival communities. To achieve cooperation and cohesion at the community level, they replaced two-at-a-time grooming with communal music in the form of singing, chanting, dancing and drumming that could emotionally engage whole community at once. In the process, the larynx migrated to a lower position in the neck to enhance their vocal range and their brains enlarged to enhance collective social interaction, which together accelerated the conversion of simple language to complex language. Complex language conferred the ability to exchange third party information and develop Theory of Mind, further enhancing strategic planning capabilities. During this process, *slow thinking* and reasoning emerged as a nonviolent means for individuals in the community to argue and persuade others to follow their self-serving *fast thinking* intuitive judgements, accounting for the prominent confirmation bias in individual reasoning. Despite flawed individual reasoning, however, wise collective reasoning emerged in those communities whose members remained open and flexible enough to arrive at a consensus after considering the most compelling arguments from both proponents and opponents. The more cooperative communities achieved the criteria for the Wisdom of Crowds and thereby made better decisions that gave them a survival advantage over less cooperative rival communities. Wise collective decision-making further facilitated the development of technology, including weapons, which sealed the dominance of cooperative human communities over both less cooperative rival communities and the rest of the animal kingdom. The concepts of rhythm, intervals, counting and ratios inherent to music and dancing were later formalized into the development of mathematics and mathematical reasoning, further enhancing their technological prowess.

Socrates: That's a fine summary, Moses, well-done! What do you think – can you spot any major weaknesses?

Moses: Now that I think about it, the statement that *"The more cooperative communities achieved the criteria for the Wisdom of Crowds and thereby made better decisions that gave them a survival advantage over less cooperative rival communities"* is a pretty critical assumption. Those early cooperative human communities would have to have been organized in a way that met the criteria of decentralization, diversity, independence and aggregation needed for Wisdom of Crowds to emerge. How likely is that to have been the case?

Socrates: What makes you think that it wouldn't be the case?

Moses: Because if a dominant alpha leader, like a head man or chief, made the important decisions, it doesn't leave much room for collective reasoning to produce the Wisdom of Crowds, does it? The leader's reasoning would be flawed by confirmation bias and merely justify his or her intuitive *fast thinking* decision. If opinions of lower-ranking individuals were ignored, how could the Wisdom of Crowds emerge? Hard to see how that scenario would confer much of a strategic survival advantage for the community as a whole!

Socrates: You are right, Moses, the alpha hierarchy scenario would not be the ideal arrangement for achieving the Wisdom of Crowds.

Moses: So how do we get around that?

Socrates: Fortunately, we don't have to. Complex language took care of it.

Moses: How?

Socrates: Think about it. What do humans use complex language for?

Moses: Lots of things – to communicate information, to argue and convince others that you're right and they're wrong, to entertain people by telling stories, to make people laugh, to flirt, to threaten or cajole, to deceive – all sorts of uses.

Socrates: What about gossip?

Moses: Sure, gossip is a huge part of it. Like we already said, it replaced grooming as the main means of enhancing social cohesion. What are you getting at?

Socrates: Gossip is the key to the Wisdom of Crowds.

Moses: How?

Socrates: It's simple, really. The reason that other primates like chimpanzees form social hierarchies with a dominant alpha at the top is that they have no other choice. If one primate bullies another, the victim has only three options: to fight back, to submit or to flee. What the victim can't do, without complex language, is to complain confidentially about his or her mistreatment to other members of the group – that is, to gossip behind the alpha's back.

Moses: But don't lower-ranking primates ever form alliances and come to each other's aid when they're being bullied by a higher-ranking primate?

Socrates: Sometimes. Related female bonobos commonly form small coalitions to dominate males. In chimpanzees, communities have been observed in which two related kin, like brothers, form a coalition to keep a stronger alpha individual under control. Occasionally, chimpanzees may shame an alpha bully into ceasing an attack when they directly witness the victim being bullied [126]. For the most part, however, an adult chimpanzee can't reliably depend on other members of the group for protection if challenged by a stronger and more aggressive individual. All that time spent grooming just cements the existing pecking order.

Moses: But how are humans any different? We may have replaced grooming with gossip, but we still live in hierarchical societies with leaders and followers.

Socrates: Not originally.

Moses: What do you mean?

Socrates: That's what I meant before when I said that you needed to brush up on your anthropology. The earliest human communities weren't like you – they were nomadic bands of hunter-gatherers who lived off whatever the land provided. They had no permanent camps and no domesticated animals or crops, and subsisted off whatever animals and edible plants they came across as they wandered about. Anthropologists refer to them as *simple foragers*, and there are about 50 or so examples that survived into the modern era, typically in remote areas. Some of them were studied by anthropologists when they were still in a relatively pristine state, before the modern world caught up with them, like the Ju/'hoansi people (formerly called !Kung) from the Kalahari Desert in South Africa who speak that distinctive click language. Or the Inuit Eskimo people in North America. Typical simple forager bands consist of thirty to forty individuals, not that different from the size of chimpanzee and bonobo communities today, which usually don't exceed fifty. Of course, being human, they all speak complex language and use gossip, rather than grooming, to reinforce social ties within the community. They are the best candidates to model your original ancestors during the Pleistocene epoch.

Moses: Interesting, but so what?

Socrates: It's rather astounding actually. Those simple forager bands don't have any alpha leaders. The whole group acts collectively serves as the alpha. It's called egalitarianism - all for one and one for all. Not only is it completely different from non-human primates, all of whom live in alpha hierarchy communities, but it's also different from later stage human communities after they've adopted agriculture.

Moses: Are you sure? I thought that all traditional human communities had leaders, starting with head men and chiefs, and then as societies became larger and more complex, lords, kings, emperors, tyrants, dictators, oligarchs, presidents and prime ministers. Even in modern democracies, elected political leaders have much more decision-making power than the average citizen.

Socrates: All that came later, after the small simple forager bands coalesced into tribes, and tribes into chiefdoms, and chiefdoms into nations and states. Originally, there were no head men, chiefs, kings, dictators or presidents. Gossip saw to it.

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[126] **Christopher Boehm**, *Hierarchy in the Forest,* Harvard University Press, 1999.

Moses: Back to gossip, I see. Please go on.

Socrates: Anthropologists refer to it as the Egalitarian Transition. Once your primate ancestors became proficient enough with language to replace grooming with gossip, it changed everything. Grooming is great for reinforcing social status between the groomer and groomee in a nonviolent way. But with complex language, you can do more than just sweet talk each other. Lower-ranking individuals can now complain to other members of the group about being bullied by higher-ranking individuals. And most importantly, once they are able to communicate third-party information, they can complain in secret, without the alpha being aware. That's the power of gossip.

Moses: So gossip fostered scheming against the alpha?

Socrates: Exactly. Every individual would prefer to be the alpha, naturally, since the alpha gets first pick of mates and key resources. But the flip side is that if you're not the alpha, then you resent being dominated by the alpha. Once you can gossip, the strategy is obvious – secretly form a coalition with enough like-minded resentful individuals to overpower the alpha the next time he or she tries to bully a member of your coalition. And with complex language, it can be a large coalition, not just small coalitions between a few individuals like other primates. That's how gossip fits in – by allowing the many to form a coalition against the few.

Moses: So why can't the alpha just form his or her own coalition?

Socrates: The alpha could, but the problem is that he or she has no natural allies, since everyone below resents their bullying behavior.

Moses: So you are basically saying that humans gained the upper hand over the rest of the animal kingdom by conniving against the alpha?

Socrates: Amusing, isn't it, that your nobler qualities, like sharing, empathy, fairness, compassion and sense of justice originated from ganging up on bullies to put them in their place, made possible by the power of gossip?

Moses: Not very flattering, but I guess it makes sense. If you say nice things to a bully, it just cements your social rank, like grooming. On the other hand, if you speak up and complain about the bully to his or her face, you will have to face the consequences then and there. But if you can secretly gossip behind the bully's back with other members of the group who also resent the bully, and succeed in incurring their sympathy and support, then the bully's days are numbered.

Socrates: Exactly – that's the power of being able to share third-party information out of earshot of the alpha. The collective resentment against being bullied by a domineering alpha outweighs the ability of any one individual to dominate the others. As a result, the alpha position becomes inherently unstable - no alpha bully can stay on top. Pretty soon, no one even wants to claim the top slot, because they realize what the inevitable consequence will be. Since the most powerful coalition is the whole group, the group collectively becomes the alpha. And that's precisely what your anthropology colleagues have found among simple forager bands across multiple continents.

Egalitarianism is the rule, vigilantly enforced by a system of status leveling mechanisms designed to suppress any upstart who tries to behave like an alpha.

Moses: What are status leveling mechanisms?

Socrates: Cultural traditions designed to dissuade individuals from behaving like alphas. They are what evolutionary biologists call *memes*. Richard [127] coined the term to refer to beliefs or behaviors communicated from individual to individual to transmit cultural ideas and practices. He shortened it from the Greek word *mimeme*, meaning *imitated thing,* so that it would rhyme with *gene*. The idea is that biological evolution proceeds through transmission of genes, whereas cultural evolution proceeds through propagation of memes.

Moses: And by propagation, I assume that you mean through language, for humans at least?

Socrates: How else? Your biological genes are physical entities that replicate by sexual reproduction, but cultural memes are conceptual ideas, not physical entities. To replicate, memes depend on language to spread them throughout the community as third party information.

Moses: Can you give me some examples?

Socrates: Sure. Richard [128] described a number of status levelling mechanisms from his time living among the Ju/'hoansi people (!Kung) in the Kalahari Desert in the 1970s. Here's how he recalled a conversation with one of the Ju/'hoan elders, together with his interpretation:

> *"Say a man has been hunting. He must not come home and announce like a braggart, "I have killed a big one in the bush!" He must first sit down in silence until I or somebody else comes up to his fire and asks, "What did you see today?" He replies quietly, "Ah, I'm no good for hunting. I saw nothing at all….maybe just a tiny one." Then I smile to myself because I now know that he has killed something big."*
>
> A proud hunter's heavy use of denial and euphemism demonstrates the degree to which the group is able to intimidate its more prominent achievers. And even after his show of modesty, other band members preemptively take pains to put down the hunter. When they go to carry in the kill, they express their "disappointment" boisterously.

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[127] **Richard Dawkins** (b. 1941) is an English ethologist, evolutionary biologist, and author. He is an emeritus fellow of New College, Oxford, and was the University of Oxford's Professor for Public Understanding of Science from 1995 until 2008. The word **meme** is a shortening (modeled on gene) of mimeme (from Ancient Greek μίμημα pronounced [mí:mɛ:ma] mīmēma, "imitated thing," a term that he coined in his book *The Selfish Gene* (1976) as a concept for discussion of evolutionary principles in explaining the spread of ideas and cultural phenomena

[128] **Richard B. Lee**, Department of Anthropology of the University of Toronto, quoted from C. Boehm, *Hierarchy in the Forest*, Harvard University Press 1999, pp. 45-47

> *"You mean to say that you have dragged us all the way out here to make us cart home your pile of bones? Oh, if I had known it was this thin, I wouldn't have come. People, to think that I gave up a nice day in the shade for this. At home we may be hungry but at least we have nice cool water to drink."*
>
> The actual feelings of the critics, who simultaneously are joking and deadly serious, is revealed in the words of a culture member:
>
> *"When a young man kills much meat, he comes to think of himself as a chief or a big man, and he thinks of the rest of us as his servants or inferiors. We can't accept this. We refuse one who boasts, for someday his pride will make him kill somebody. So we always speak of his meat as worthless. In this way we cool his heart and make him gentle."*
>
> The speaker is a famous healer, and obviously, an eloquent indigenous political philosopher. He is a student of human nature as well, and an astute one. He seems to be saying that legitimate male accomplishments may lead to inflated self-opinion and tendencies to dominate, and that with these proclivities, men are likely to engage in homicide. Let us take these principles as a working hypothesis for any group of humans whose males are hunters."

He goes on to comment:

> "As with other forager groups (see Kelly, 1995), hunting prowess brings great respect among the !Kung because large-game meat is shared by all households within the band. As tabulated by Lee (1976:244), there is great variability among men as to whom is responsible for the kill. They use two principal mechanisms to keep the best hunters from dominating the politics of the camp and monopolizing the women. We have seen that they preemptively cut down those who might become arrogantly boastful. They also share all large game meat, helping those who are incapacitated or down on their luck, and these customs are enhanced by some very practical cultural rules.
>
> Credit for the kill goes to the owner of the first arrow to hit the game. This man (who may not even have been present) has to distribute the meat formally to all household heads in the band – a task associated with not only prestige, but tension. Because the !Kung trade arrows often (Wiessner, 1996), the responsibility of owning the meat while it is distributed is randomized, thereby preventing the more successful hunters from presiding over their own accomplishments. In effect, it is a way of removing the temptation to dominate. The fact that the best hunters speak so modestly, and frequently swap arrows to avoid envy, is a monument to the efficacy of ridicule as an instrument of social control. But as we shall see, if they are faced with serious upstartism, people like the !Kung will go far beyond ridicule."

That's the egalitarian credo - if you can't be the alpha yourself, then the next best option is to be one among equals. The status leveling mechanisms like ridicule, shaming, randomization of meat distribution and arrow sharing are all designed to suppress alpha-like behavior nonviolently.

Moses: So they really make all major decisions by consensus, without a dominant alpha like a head man or chief?

Socrates: Yep. It's remarkably consistent. No matter where simple forager communities have been studied - Africa, the Arctic, the Americas, Australia – close to 50 examples in all, egalitarianism is the rule [129]. Head men, chiefs and other authoritarian leaders don't appear until humans begin domesticating animals and growing crops starting about 10,000 years ago with the Agricultural Revolution. The implication is that the human race has spent most of its time on earth so far living in egalitarian communities, so I wouldn't underestimate its influence on your subsequent cultural development, even after your return to hierarchical societies.

Moses: What happened with agriculture that made us return to social hierarchies?

Socrates: Agriculture made it possible for human communities to grow much larger – in fact, too large for egalitarianism to remain practical. The size of simple forager communities is limited by the local availability of game to hunt and edible vegetation to forage, and usually is less than hundred or so individuals. With cultivation of crops and livestock, the size of human communities can obviously grow much larger, to many hundreds or thousands or millions of people as bands coalesced into tribes and tribes into states. In those larger communities, consensus decision-making where everyone has an equal say becomes too unwieldly for egalitarianism to be practical. Simple forager bands, on the other hand, are small enough for each hunter to have an independent say in making major decisions by consensus, like where to move to next or when to go to war. Some hunters are more influential than others, but they risk being ridiculed, banished or even executed if they try to boss others around.

Moses: What about the women? Do they share power equally with the male hunters?

Socrates: No. Women, as well as men who choose not to hunt, don't have the same standing.

Moses: So it's not completely egalitarian then. Sounds pretty sexist, in fact.

Socrates: I didn't claim it was utopia. Egalitarian simple forager bands are also more violent than modern human societies, since status leveling mechanisms are not always effective at defusing violence. In fact, murder rates are about 10-fold higher than in modern human societies. And not just from warfare with other bands, but also from murders within the same band over infidelity and other disagreements. Egalitarianism puts a high premium on personal freedom, but also on personal responsibility. There's no formal justice system to mediate

[129] **Christopher Boehm**, *Hierarchy in the Forest,* Harvard University Press, 1999.

grievances, which means that vengeance is a private matter that an individual, family or a band must take into their own hands. If someone in your family is killed, your family is honor-bound to extract revenge, and then the other person's family extracts revenge on your family, and so forth.

Moses: Sounds less stable than an alpha hierarchy. I'm pretty sure that chimpanzees and bonobos don't have honor killings.

Socrates: You are right. But even so, overall murder rates in human simple forager bands are similar to chimpanzee communities - roughly 20 per 10,000 individuals per year. And if you factor in nonlethal violent confrontations, which are about 200-300 times more frequent in chimpanzee communities, human simple forager bands are actually less violent overall.

Moses: I'm not sure that's exactly an improvement. If the overall murder rates are the same but violent confrontations are 200-300 times more frequent, that just means that chimpanzees are 200-300 times less likely to kill each other during a violent confrontation.

Socrates: Which is a testament to how effective those cultural status levelling mechanisms are at nipping violent confrontations in the bud, before they become lethal. Of course, unlike chimpanzees, human simple foragers have weapons at their disposal. That's why the risk of a confrontation escalating to murder is inherently so much higher in humans.

Moses: Ah, I see what you mean. Lucky for chimpanzees that they aren't smart enough to use weapons.

Socrates: Do you really think that chimpanzees aren't smart enough to use weapons?

Moses: How else can you explain it?

Socrates: Doesn't it seem odd to you that chimpanzees, as well as many other primates, are clever enough to devise simple tools, like poking a branch into a termite mound to extract termites, or using rocks to smash nuts open? Yet if you give an angry chimpanzee a stick, they may wave it around in a threatening way, but it never seems to occur to them to actually use it as a club or a spear to attack an opponent. Same with rocks – chimpanzees are accomplished nut smashers, but it never seems to occur to them to use a rock to smash an opponent's head. One good blow to the head and the contest would be over.

Moses: I've never really thought about it, but now that you mention it, it does seem a bit odd. If they commonly use other objects as tools, it seems like a pretty small leap to use a stick or rock to gain an advantage over an opponent. I wonder why.

Socrates: Perhaps because weapons are a different kind of tool.

Moses: What do you mean?

Socrates: Primates use tools that are beneficial to everyone, like getting at food by poking a stick into a termite mound – a *win-win* for everyone. But weapons are different - they give you potentially lethal power over other individuals.

Moses: Weapons create *win-win* situations for the group too. Like for defending against predators, waging war or hunting game.

Socrates: True, but first the members of the group have to agree not to use the weapons against each other. That's the rub.

Moses: What do you mean?

Socrates: As social animals, your original human ancestors lived in communities like your great ape cousins today. With chimpanzees, a single male, or less commonly a coalition of a few related males, dominate as the alpha, with the other males and females arranged in a pecking order. With bonobos, it's typically the opposite. Small coalitions of related females dominate the males. Either way, all of today's non-human primates live in alpha hierarchies in which the higher-ranking individuals deal it out and the lower-ranking individuals take it. If an individual doesn't like their position in the pecking order, they can challenge a higher-ranking individual, but they typically have only themselves to depend on. If they lose, they are out of luck and have no choice but to slink back to the same position that they started from. So let's say that you are a clever chimpanzee living in an alpha hierarchy, and it has just occurred to you to use a heavy stick as a club the next time the alpha bullies you. Or even better, wait for him to fall asleep and then crack his skull open with a rock. What happens the first time you use it?

Moses: Hopefully, you would teach the alpha a lesson!

Socrates: Yes, but then what?

Moses: It might be a short-lived victory, since whoever sees you use the tool as a weapon could copy you.

Socrates: Exactly! Once weapons enter the scene, no alpha is safe. When all you have at your disposal are kicks, bites and scratches, it's pretty hard to defeat an alpha who is bigger, stronger and more aggressive than you, even with the element of surprise. But once it occurs to you to use a club or a rock as a weapon, all that you really need to do is wait until the alpha falls asleep, and crush his skull with one good blow.

Moses: What you're saying is that the first instinct of a primate living in an alpha hierarchy would be to use a weapon to advance their standing in the hierarchy. And that creates civil war by destabilizing the alpha position.

Socrates: Exactly. That's why you don't see chimpanzees or bonobos using weapons. It's not that they're not smart enough. They use other objects as tools all the time, but weapons would unleash civil war.

Moses: How can you know if that's really the truth?

Socrates: You don't see any other primates using weapons, do you? That means that either the idea of using a tool as a weapon has never occurred to them, or if it did, the consequences were disastrous enough for natural selection to eliminate those communities (Figure 17-1).

Moses: So our common ancestors who continued to live in alpha hierarchy communities couldn't develop weapons without self-destructing. But without weapons, they were left at a tremendous disadvantage compared to our common ancestors who adopted egalitarianism and could handle weapons.

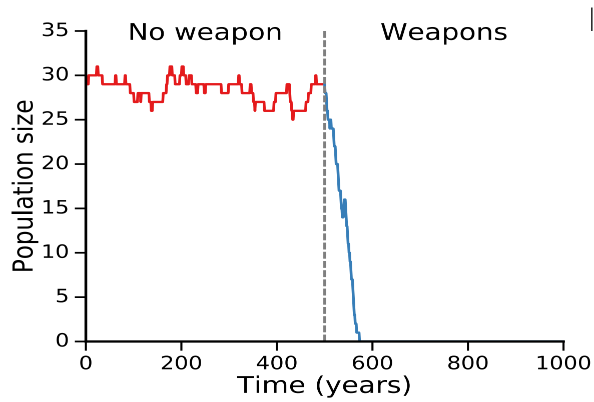

Figure 17-1. The simulated effects of introducing weapons into a chimpanzee community. Based on birth, death, and in-group murder rates extracted from studies comparing wild chimpanzee and simple human forager populations, the chimpanzee community size before the introduction of weapons remained stable for 500 years. At 500 years, the introduction of weapons (dashed line) was simulated by increasing the mortality associated with violent challenges by a factor of 200 (from 0.002 to 0.400/individual/year). The resulting increase in total death rate (to 0.465/individual/year) outstripped the birth rate (0.067/individual/year), leading to extinction of the community within 90 years. Adapted from Calmettes, G. and J. N. Weiss. The emergence of egalitarianism in a model of early human societies." *Heliyon* **3**(11): e00451, 2017.

Socrates: Exactly. That's the key difference – egalitarianism psychologically pre-conditioned the community to restrict weapon use for the common good, rather than for elevating social rank. That's why the Egalitarian Transition was so critical for your ancestors – it set the stage so that your ancestors could adapt tools into weapons.

Moses: So natural selection took care of it. The weaponized hunter-gatherers who stuck with alpha hierarchies ended up murdering each other with their primitive weapons, whereas the egalitarian hunter-gatherers who respected each other as equals were able to reserve the use of weapons to achieve common goals.

Socrates: That's as good an explanation as any, both for why present day simple forager bands are all egalitarian and why non-human primates don't use tools as weapons. Weapons make it too easy to kill the alpha. But if you can get over that destabilizing hurdle, the ability to kill from a distance is a huge advantage. That's why humans can afford to be such so much physically weaker, slower and less ferocious than almost any other mammal of the same size.

Moses: So gossip really was the key! It made alpha hierarchies unstable, which flipped the power structure by 180 degrees to egalitarianism, in turn making it possible to invent weapons and use them for the common good instead of civil war.

Socrates: I couldn't have said it better myself.

Moses: I guess you've also answered my previous question about the influence of the Wisdom of Crowds shaping human civilization. With each hunter having an equal say in decisions that impacted the whole band, egalitarianism met the essential criteria of decentralization, independence, diversity and aggregation required for Wisdom of the Crowds to emerge!

Socrates: Exactly. When one of the hunters proposed a plan, the other hunters would use their *fast thinking* intuition to decide impulsively whether they agreed or disagreed. Then they would turn to their *slow thinking* biased reasoning to come up with a good set of arguments in favor of the plan if they agreed, or a good set of counterarguments if they disagreed. If everyone had an equal say and an equal vote, the most compelling set of arguments would win the day and the Wisdom of Crowds would prevail! A well-reasoned consensus decision by all of the hunters, instead of an impulsive *fast thinking* intuitive decision by an individual alpha leader whose own reasoning is contaminated by confirmation bias!

Moses: All in all, then, our human ancestors who transitioned to egalitarianism gained two major advantages over the ones who didn't. Egalitarianism allowed them to adapt tools into weapons without exterminating themselves, and also to fulfill the criteria for the Wisdom of Crowds to emerge from collective reasoning, in spite of their flawed individual reasoning.

Socrates: Positive feedback, just like you'd expect for an evolving bottom-up process. Natural selection rewarded human simple forager bands that made wise consensus decisions through collective reasoning and penalized those that made poor consensus decisions. That evolutionary process undoubtedly played a role in honing the criteria required for the Wisdom of Crowds to emerge. Superior collective reasoning also facilitated faster technology development, including the invention of weapons. Then weapon development fed back to reinforce egalitarianism by making the individual alpha position even more unstable, since once weapons made it possible to kill at a distance, an alpha was no match for a coalition. "Coalition enforcement theory," as Paul calls it [130]. Once that switch was flipped, there was no turning back!

Moses: The switch that paved the way for man's technological superiority and dominance over the rest of the animal kingdom!

Socrates: A very common theme in nature – once you reach a certain threshold and engage positive feedback, the whole system suddenly rearranges itself into a new configuration. Instead of a gradual transition in which the alpha is slowly replaced by larger-sized and larger-sized coalitions until finally the whole community serves as the alpha, it happens all at once. One minute it's an alpha hierarchy and the next it's fully egalitarian. Emergence in action!

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[130] **Paul M. Bingham**. Human evolution and human history: A complete theory. *Evol Anthropol*. 9:248-257, 2000.

Moses: And you said that human simple forager societies all over the world, living in completely different environments ranging from the tropical rain forests to deserts to the artic, have all have evolved a similar egalitarian culture, right? That does sound like some universal principle is at work, suddenly flipping the power structure from an alpha hierarchy to egalitarianism. It sounds almost like a phase transition.

Socrates: How so?

Moses: I was thinking of an ice cube. As long as the temperature remains below freezing, intermolecular hydrogen bonds immobilize the water molecules in a rigid array, just like the rigid pecking order in an alpha hierarchy. At the melting point, however, the vibrational motion of the water molecules becomes too great for the hydrogen bonds to hold the molecules together, and the rigid structure dissolves. The water molecules then swirl freely around each other. Gossip is like temperature – when it becomes hot enough to enable resentment-based coalitions to form, the rigid power structure breaks apart and power-sharing becomes liquid.

Socrates: Very clever metaphor, Moses, I like it - a thermodynamic analogy for the Egalitarian Transition! Yin and Yang at work! An attractive element holding the structure in place, a repulsive element trying to pull it apart and a coupling element linking the two. Both illustrating the same universal organizing principle, even though the details couldn't be more different.

Moses: I'm glad that you like it, but let's not get too carried away. Three elements might be enough to explain the ice cube melting, but I doubt that something as complex as the Egalitarian Transition can be condensed into just three elements. After all, it involves an incredibly complicated interplay between a whole slew of factors, from genes and biological networks to memes and social networks – networks upon networks all feeding back on each other.

Socrates: Don't be so sure. As Leonhard showed, the best way to analyze networks is to strip away all of the myriad details and keep just the essential conceptual elements. If you want to understand the Egalitarian Transition conceptually from the 10,000 foot view, search for an attractive element holding the alpha hierarchy together, a repulsive element trying to break it apart, and a coupling element linking the two.

Moses: Where do you even start?

Socrates: The first rule is to think simply. As Albert would say,

> "Everything should be as simple as possible, but not simpler!"

The second rule is to think conceptually. Remember, it's the conceptual essence that we're after, not the endless details of the myriad networks that you just rattled off. If we put our minds together, I bet that we can come up with a plausible hypothesis. Want to give it a try?

Moses: Sure, why not?

Socrates: Then suppose we start with a hypothetical community of primates arranged in an alpha hierarchy. Which one will be at the top?

Moses: I suppose the most aggressive individual who has the greatest desire and physical ability to dominate the others.

Socrates: Very good. Let's call that the attractive element – the aggressiveness factor α that strives keep the current hierarchical pecking order in place. Now what's a repulsive element trying to break down the hierarchy?

Moses: I suppose that the lower-ranking primates resent being bullied by the alpha and other higher ranking primates. They'd be happy to have the pecking order rearranged if it would improve their status.

Socrates: Then let's call that the bitterness factor β, resentment against being bullied by the alpha and other high-ranking primates. What next?

Moses: The primate with the greatest desire/physical ability to dominate and the greatest resentment against being dominated would be the alpha at the top. So maybe we could take the sum of $\alpha + \beta$ to determine each primate's rank in the pecking order, with top-ranking alpha having the largest sum and the lowest-ranking primate the smallest sum.

Socrates: Excellent. See, that wasn't so hard! Now we have our first two elements, the attractive α factor maintaining the hierarchy and repulsive β factor trying to pull it apart. All we need now is the coupling element that links the two.

Moses: I suppose that could be where gossip comes in. Gossip allows lower-ranking primates to communicate with each other out of earshot of the alpha and form a coalition against the alpha. We can call it the gossip factor γ.

Socrates: Perfect – you have all three conceptual elements: α, β and γ.

Moses: Now what?

Socrates: How about we take the individual $\alpha + \beta$ values for all of the primates except for the alpha, and add them together? If that sum is greater than alpha's $\alpha + \beta$ value, then their combined aggressiveness and resentment at being dominated would exceed that of the alpha. In other words, they could overpower the alpha, if only they had the communication skills to form a coalition and come to each other's aid if the alpha bullied them.

Moses: Then why don't we multiply the coalition's $\alpha + \beta$ sum by γ, to reflect the probability that gossip skills are sufficient for a coalition to form. Then it's obvious that there will be a critical value of γ between 0 and 1 at which the coalition's $\alpha + \beta$ sum multiplied by γ becomes greater than any individual $\alpha + \beta$ sum, including the alpha. That's the point at which a coalition becomes more dominant than the alpha. Once γ reaches that critical value, it will be in the interest of the alpha to join the coalition and share power, rather than be bullied by the more powerful coalition (Figure 17-2)!

Socrates: Excellent *slow thinking*, Moses! And not only that, it will also be in the direct self-interest of all the other primates to avoid behaving like a dominant alpha, since provoking resentment and angering the coalition will result in punishment and a fall in rank.

Moses: And using complex language, the primates could codify which behaviors are acceptable and which are not, so that the rules could be communicated to all members of the group. That can explain how those cultural status leveling mechanisms came into play - ridicule, ostracism and shunning to put down upstarts preemptively before their behavior escalates to violence! Basically, they are the origin of moral beliefs.

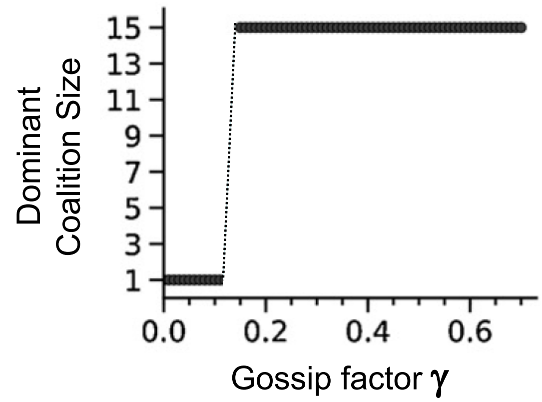

Figure 17-2. The Egalitarian Transition in the α–β–γ (aggressiveness-bitterness-gossip) model of a primate community. The primate community suddenly transitioned from a single dominant alpha leader with the highest α+β sum (coalition size 1) to an egalitarian coalition of all 15 individuals when γ reached a value of 0.1. Modified from G. Calmettes and J. N. Weiss. "The emergence of egalitarianism in a model of early human societies." Heliyon 3(11): e00451, 2017.

Socrates: Very good. The hunter restrains himself from bragging about his kill because he knows that the cultural memes dictate that he will be ridiculed and punished if he does. And at the community level, the benefits of large scale cooperation among the hunters promoted by status leveling memes allows weapons to be developed to hunt large game, to defend the community against predators and to wage warfare.

Moses: Not bad! We did it - the Egalitarian Transition reduced to three elements, the repulsive and attractive elements α and β, and the coupling element γ [131]. Same principle as our melting ice cube!

Socrates: One difference, though. When an ice cube melts, all the water molecules end up in an equivalent state. But in the Egalitarian transition, not all of the primates are equivalent, what with women and male non-hunters being relegated to an inferior political status.

Moses: That is curious. Why do you suppose females didn't get an equal share of power as the male hunters? They share the same complex language and could form coalitions just as easily as the hunters.

Socrates: That question also puzzled me for a long time, until it occurred to me to think of it in terms of game theory.

[131] For detailed development of this simple model of the Egalitarian Transition, see G. Calmettes and J.N. Weiss. The emergence of egalitarianism in a model of early human societies. *Heliyon* 3(11): e00451, 2017.

Moses: Game theory?

Socrates: Yes. Ever heard of the Public Goods Game? It's similar to the Prisoner's Dilemma game except that it involves more than just two players.

Moses: How does it go?

Socrates: Let's say there are 5 players, and each one gets $20. The rules state whatever portion of the $20 that a player donates to the public good will produce a payoff that is subsequently distributed equally among the five players. For example, if each player donates their full $20 to the public good and the payoff is 50%, the donated $100 will yield $150, which is then divided 5 ways among the players, or $30 for each player. But if no one donates, each player ends up with the same $20 that they started with.

Moses: In that case, the winning strategy is pretty obvious - always donate your full holdings to public good, since it maximizes the return for everyone.

Socrates: Correct. It's a positive sum game, and the strategy that yields the highest payoff is to cooperate fully on each round. But now imagine that the rules change and the payoff on the donated resources is eliminated. What's the best strategy then?

Moses: Then there would be no advantage for anyone to donate $20 to the public good. If every player cooperated, the donated $100 would remain the same, and each player would get back their $20. No gain for anyone.

Socrates: Not only that, it would also be risky for any individual player to donate to the public good – when the total is divided by five, if you were the only player to donate your $20, you'd end up with only $4, whereas the other fourplayers would increase their holdings from $20 to $24.

Moses: Good point. In that case it's a zero sum game in which there's no benefit in donating to the public good. Moreover there's a risk of being penalized if you do.

Socrates: Exactly. Unlike a positive sum game, the rational strategy in a zero sum game is to be selfish and not cooperate.

Moses: Makes sense. So how does this relate to our sexist hunter-gatherers?

Socrates: Because the male hunters can only succeed in bringing down large game if they cooperate with each other. The energy that they spend hunting has a much higher payoff when they hunt collectively as a team than independently as individuals.

Moses: Ah, I see. So it's equivalent to a positive sum game in which the highest payoff depends on the hunters cooperating fully with each other, like donating your $20 to the public good and getting back $30.

Socrates: Exactly. Now what about gathering – is it also a positive sum situation?

Moses: Not really. You can't cover as much ground if everyone sticks together in one big group searching for the same fruits, nuts and small animals. It's more effective for gatherers to go their separate ways.

Socrates: In other words, instead of a positive sum game like the hunters, the gatherers are playing a zero sum game, in which there is no payoff and maybe even a penalty for cooperating.

Moses: That means that the hunters do best by cooperating, including sharing the meat equitably to everyone's benefit. But the gatherers have no real incentive to cooperate. They each go their own way and keep what they find for their immediate family.

Socrates: In fact, that's exactly how the Ju/'hoansi [!Kung] behave. As Christopher [132] explains:

> "Sharing of meat is by no means solely a political or social act. Kelly (1995) has discussed the widespread practice of sharing large-game meat as a means of reducing variation of protein intake at the family level, and it appears then even the better hunters' intakes might be sporadic without this practice. Precisely because the actuarially sophisticated system of sharing could lead certain men to feel superior to others, a variety of practices and customs have been created to "cool their hearts" in the words of the !Kung. It is worth noting that hunter-gatherers on other continents have invented similar practices to randomize the ownership of large-game kills (Wiessner 1996), surely for similar motives. A very successful hunter potentially poses a political danger to the band, and the band takes step to reduce such problems even as a cooperative sharing is facilitated."
>
> "Lee's is one of the richest descriptions we have of how hunter-gatherers preemptively put down potential upstarts in their midst. Such behavior is not reported to be regularly directed at women, who forage for plant foods that are often just for family use and capture only small animals that normally are not shared with the entire band. With less prestige attached to their daily work, women are not in danger of trying to turn proficiency at food production into political power. The same applies to men when they gather plants or capture rodents."

In other words, meat is highly prized for its high nutritional value and therefore associated with more prestige than gathering fruits, nuts and vegetables. But hunting large game to obtain meat is inherently more risky and requires a high level of cooperation to achieve the best payoff. That incentivizes the male hunters to form a powerful coalition among themselves, which they enforce by status leveling mechanisms that discourage the superior hunters from behaving like alphas and ensure that large-game meat gets shared equitably. The women or men who don't hunt, on the other hand, are primarily gatherers, for whom cooperation is not rewarded with a high payoff, weakening the incentive to form coalitions of their own. So the male hunters end up as the powerful collective alpha coalition, with no real incentive to share power with women performing less hazardous and less prestigious work. That's how women ended up with the short end of the stick.

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[132] **Christopher Boehm**, *Hierarchy in the Forest*, pp. 45-47, quoted from Lee (1979:244-246).

Moses: Why didn't the women become hunters too, to avoid becoming second class citizens? Do you think it's because they are physically weaker or were too busy raising children?

Socrates: I doubt it. Richard [133] attributes it to a very practical reason. Hunter-gatherers depend vitally on both hunting and gathering. If the hunters spend all day hunting and are unsuccessful, they would return to camp hungry with no prospect for a dinner were it not for the gatherers collecting edible foods during the day and preparing a cooked meal for their return. That dependable meal from the gathered food provides them with the energy to go out hunting again the next day, until they are successful. Without the gatherers, the whole community would starve should the yield from hunting decrease even temporarily. So the community cannot afford to have everyone, male and female, as full-time hunters. They depend vitally on the gatherers as well. Cooking with fire was also a big factor, since cooking greatly increases the calories released during digestion of fruits, vegetables and meat. But someone has to stay home to prepare and cook the gathered food.

Moses: Even so, why don't the males and females share the hunter and gatherer roles, instead of segregating them by gender?

Socrates: Simple – it's because women are smarter than men.

Moses: What's that supposed to mean?

Socrates: Can you imagine a group of male and female hunters armed with flimsy spears seeing a mammoth in the distance, and one of them saying "I bet if we can sneak up on it, we can kill it"? Being intelligent and sensible, the woman's answer would be "You can't be serious?" Only a much less intelligent and reckless male would say "Great idea, let's go for it!"

Moses: I see your point. Ergo the origin of sexism in early human communities, setting a precedence that's been hard to break ever since. It's a shame, really. If the women's opinions had been given equal weight with the male hunters, they would undoubtedly have further strengthened the Wisdom of Crowds by enhancing both the *decentralization* and *diversity* criteria.

Socrates: I wouldn't be so quick to conclude that the female input was ignored. Since most simple foragers are monogamous, the wives undoubtedly exerted a significant influence on the *slow* thinking reasoning of their husband hunters. So probably the women's contribution to wiser decision-making was just as important as the men's, even if not explicitly acknowledged.

Moses: Good thought, that's probably closer to the truth.

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[133] **Richard Wrangham,** *Catching Fire: How Cooking Made Us Human,* Basic Books, 2009.

Socrates: I'd say that we covered a lot of ground in working through our hypothesis, even if it is subject to our own confirmation biases. Perhaps you can put it all into a final summary?

Moses: Sure, happy to. Here goes.

- When our human ancestors left the safety of the trees four to eight million years ago, survival on the ground required a higher level of cooperation between members of the community in order to defend themselves against predators and competing primates (Figure 17-3).
- Initially, social cohesion at the community level was enhanced by supplementing grooming between pairs of individuals with communal music in the form of singing, chanting, dancing and drumming.
- In the process, the larynx migrated to a lower position in the neck to enhance their vocal range and their brains enlarged to enhance collective social interaction, which synergistically accelerated the conversion of simple language to complex language.
- Complex language conferred the ability to exchange third party information and develop Theory of Mind, the key prerequisites for gossip, allowing members of the community to harness their resentment against being dominated by alpha individuals by forming coalitions that were powerful enough to overpower any would-be alphas.
- Destabilization of the alpha hierarchy led to the Egalitarian Transition in which male hunters (but not gatherers) shared power equally, enforced by cultural memes in the form of status leveling mechanisms designed to suppress alpha behavior.
- *Slow thinking* and reasoning emerged as a nonviolent argumentative tools for individuals to persuade others to follow their self-serving *fast thinking* intuitive judgements, accounting for the prominent confirmation bias in individual reasoning that lasts to this day.
- However, because the egalitarian credo mandated respect for each hunter's opinion, whether for or against the proposed judgement, collective reasoning led to well thought-out consensus decisions meeting the criteria of decentralization, diversity, independence and aggregation critical for the Wisdom of Crowds to emerge.
- Wise collective decision-making enhanced strategic planning capabilities and supported advances in technology, including weapons, which sealed the dominance of egalitarian simple foragers over hierarchical simple foragers and other predators.
- Positive feedback between all of these elements strengthened the egalitarian credo into a codified moral belief system.
- The concepts of rhythm, intervals, counting and ratios inherent to music and dancing were later formalized into the development of mathematics and mathematical reasoning.

How's that?

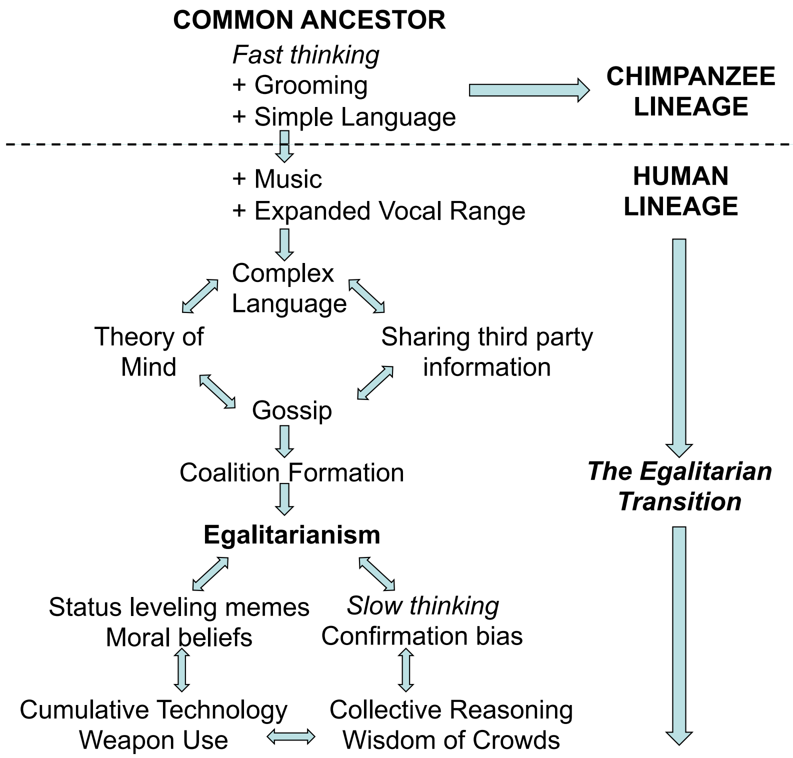

Figure 17-3. Hypothetical model of human evolution. See text.

Socrates: I think that you covered all the key elements, although you failed to mention the thermodynamic analogy of the Egalitarian Transition to a phase transition like our melting ice cube.

Moses: Actually, I didn't mention it on purpose.

Socrates: Why not?

Moses: Remember the quote from Albert about models, "Everything should be as simple as possible but not simpler".

Socrates: What about it?

Moses: The "not simpler" part. As fond as you are of the idea that everything in nature can be reduced to your Yin and Yang Axiom, I'm still a bit skeptical that something as complicated as the Egalitarian Transition can be condensed, even conceptually, into just three elements.

CHAPTER 18: The Cooperation Conundrum

Socrates: So your concern is that our $\alpha-\beta-\gamma$ model is oversimplified?

Moses: Exactly. It seems to me that there could be many other factors besides aggressiveness, bitterness and gossip that helped trigger the Egalitarian Transition.

Socrates: What do you have in mind?

Moses: Take gossip, for instance. Maybe it wasn't complex language in the form of gossip that drove the Egalitarian Transition, but the other way around. Maybe cognitive development made it obvious to our ancestors that they could accomplish more by cooperating with each other than behaving like alphas. Or maybe they cooperated in order to defend themselves more effectively against predators or attacks from rival simple forager bands. Or maybe once they invented weapons, the ability to bring down large game was the incentive to cooperate, in order to provide a steadier diet for everyone by sharing meat. Perhaps we put the horse before the cart – maybe complex language didn't cause the Egalitarian Transition, but resulted from it.

Socrates: Excellent points, Moses. All of those factors were certainly important in strengthening the egalitarian culture in human simple foragers. But the basic question that we've been trying to answer is this - what originally triggered the Egalitarian Transition, in distinction to what synergistically reinforced it by positive feedback once it occurred? We already argued that weapons had to come after the Egalitarian Transition, or else your original human ancestors would have destroyed themselves by using them against each other to better their position in the alpha hierarchy (Figure 17-1). The question that you're really asking, though, is whether early humans somehow evolved a personality compatible with large scale cooperation first, even before complex language and gossip entered the picture. Unfortunately, there's a big problem with that theory.

Moses: What's that?

Socrates: The question of how cooperation arises, especially flexible cooperation on a large scale between genetically unrelated individuals. It's been a major puzzle ever since Charles first proposed natural selection as the guiding principle of evolution.

Moses: You mean another unsolved paradox in evolutionary biology?

Socrates: I suppose that you could call it that, but I prefer the *Cooperation Conundrum*.

Moses: Why?

Socrates: As the two of your leading evolutionary biologists succinctly put it [134]:

[134] **David S. Wilson** and **Edward O. Wilson**. Rethinking the theoretical foundation of sociobiology. *Q Rev Biol*. 82:327-48, 2007.

> "Within groups, selfishness beats altruism. Altruistic groups beat selfish groups. Everything else is commentary."

Moses: What's that supposed to mean?

Socrates: It means that for social animals, there's competition both within groups and between groups. As far as between-group competition is concerned, no one disputes that a group of cooperative individuals who put the common good before personal interests will outperform a group of selfish individuals who squabble among themselves. The problem, however, arises from the within-group competition.

Moses: How so?

Socrates: The issue revolves around how the dynamics of within-group competition can ever produce a group of cooperative individuals. If only the fittest survive within the group, then why should one perform a selfless altruistic act that is costly to oneself, but benefits another? If a free-rider who behaves selfishly can enjoy the same benefits as everyone else in the group without having to pay a price, then why contribute? In the end, the selfish free-riders who refuse to share will acquire more resources than the selfless altruists. That means that when times are hard and resources become limited, the free-riders have a survival advantage over the altruists.

Moses: In other words, when the going gets tough, selfish free-riders will survive and selfless altruists will perish.

Socrates: That's the problem exactly - how can a group ever become enriched in altruistic individuals if within-group natural selection weeds out the genes conferring selfless behavior in favor of genes conferring selfish behavior? That question has vexed evolutionary biologists for more than a century now.

Moses: I can see the problem from a theoretical standpoint. But there has to be an explanation, since you can't deny that humans cooperate extensively on a large scale. Not to mention a lot of other animals that also cooperate to protect themselves from predators or to hunt more efficiently as a pack.

Socrates: Even so, most evolutionary biologists today still hold that individual selection trumps group selection. It's hard to come up with a mathematical model of evolution, for example, in which group selection wins over individual selection except under very restrictive conditions. Which is not to say that group selection has no influence. It's just that it's not very robust because groups typically remain vulnerable to being taken over by selfish individuals. A compromise is to call it multi-level selection, in which the individual selection is most important factor but can influenced by selection at other levels.

Moses: Still, there must be reasonable explanations for why species cooperate.

Socrates: There are, but they're better at explaining small scale cooperation than the large scale flexible cooperation that characterizes human communities.

Moses: Like what?

Socrates: If individuals in a community are genetically related to each other, for example, sacrificing oneself so that one's kin will survive can explain how altruistic genes might be favored rather than eliminated. As J.B.S. joked:

> "Would I lay down my life to save my brother? No, but I would save two brothers or eight cousins"[135].

In other words, saving two brothers, each with half of your genes, or eight first cousins, each with an eighth of your genes, comes out even in terms of preserving your own genes. However, human simple forager bands typically contain unrelated individuals who cooperate extensively, so the kin selection hypothesis doesn't fully explain their cooperation.

Moses: What about the simple idea that if you help me, then I will help you, whether or not we are related?

Socrates: That's called the reciprocity hypothesis. However, reciprocity means paying back your debts. Unless you can trust your groupmates to reciprocate, then you are vulnerable to being cheated by free-riders, especially as group size becomes large and free-riders have more room to hide. Even in modern humans, sustained cooperation is not easy to demonstrate. The Public Goods Game is a classic example.

Moses: The same game that you proposed explains the origin of sexism in egalitarian simple foragers?

Socrates: That's the one.

Moses: How does it apply here?

Socrates: Take the positive sum version of the Public Goods Game. Remember that we gave 5 players $20 worth of resources apiece, and asked them to donate a portion to the public good. Whatever they donated generated a payoff of 50% that was then divided equally among all five players. In other words, if each player donated their full $20 to the public good, the donated $100 yielded $150, which, divided 5 ways, meant that each player now had $30. The most rational strategy yielding the highest overall return is obvious - always cooperate by donating your full holdings to the public good. But guess what happens when you play the game with real people?

Moses: What?

Socrates: A very consistent outcome.

Moses: Which is?

Socrates: At first, the players donate most of their $20 to the public good, since that's the obvious strategy that maximizes the most benefit to everyone. But after a few rounds, one sneaky player invariably decides to hold back and keep their $20 while the

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[135] Quip from 1932 by **J.B.S. Haldane** (1892-1964), a British scientist known for his work in the study of physiology, genetics, evolutionary biology, and mathematics.

other players continue to donate. Then the donated $80 increases to $120, which, divided by 5, returns $24 to each player, including the one who did not donate. The selfish player now has $44, whereas the others have only $24. In other words, each player's wealth still increases, but unequally.

Moses: Sounds like trickle down economics! I bet that the selfish player rationalizes that since everyone is still benefiting, his/her action is not harming anyone else.

Socrates: Possibly, except that when the other four players realize that they've been outfoxed, they also stop donating to the public good (Figure 18-1). From then on, contributions to the public good decline from all of the players, and the total wealth of the group stagnates.

Moses: So the selfish player ends up spoiling it for everyone. What if the others are able to punish the selfish player? Does that change the outcome?

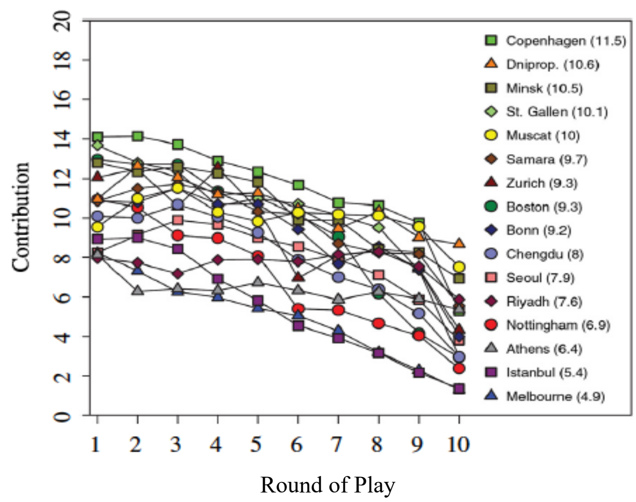

Figure 18-1. Public goods game outcomes in 15 countries. Data come from the no punishment variation. While there is substantial cross-cultural variation in contributions, contributions decline over time in almost every population. From M. Perc et al. *Physics Reports* 687: 1-51, 2017.

Socrates: Indeed, many variations of the Public Goods Game have been explored. As you just suggested, a penalty rule can be added that allows players to punish selfish players by giving up a portion of their resources, which is then also involuntarily deducted from the selfish player's resources. So if four players each decide to give up $10 on the next round to punish a selfish player, they would each lose $10 apiece but the selfish player would suffer a much greater loss of $40. Or alternatively, you can add a rule to allow players to reward good behavior in others, by giving up a portion of their own wealth to a selfless player on the next round.

Moses: What happens then?

Socrates: It helps, but it doesn't completely resolve the problem. The group typically remains vulnerable to selfish players, with the free-riders looking to take advantage of the suckers, especially when the group gets large so that free-riders become harder to identify. The best you can hope for is an outcome in which the fraction of selfless versus selfish players oscillates over time, with selfish free-riders predominating in some phases and selfless players during others.

Moses: What causes the oscillations?

Socrates: Same as always - our old friend feedback. I'm sure that if you think about it, you can figure it out. Go ahead, give it a try.

Moses: I suppose that punishment acts like negative feedback to inhibit selfish behavior. And reward acts like positive feedback to promote selfless behavior.

Socrates: Very good, Moses, you've been paying attention! Complementary interacting opposites – selfless behavior is the attractive element, selfish behavior is the repulsive element, and they are coupled together by the punishment and reward options. Under the right conditions, the feedback causes oscillations.

Moses: Still, if people recognize that the obvious strategy bringing the greatest benefit to all is full cooperation, then why don't they cooperate? Why do they behave so irrationally?

Socrates: People are not behaving irrationally. The problem is that the most rational strategy for the group is not necessarily the most rational strategy for the individual. That's a conflict.

Moses: What do you mean?

Socrates: Think of it in terms of natural selection. The rationale for selfless behavior is that if everyone cooperates, then everyone shares in the benefits, so the group as a whole is more likely to survive. However, if everyone benefits equally, then your particular genes gain no survival advantage over other genes in the group. By refusing to share, on the other hand, you acquire more resources than selfless individuals, and hence your genes are more likely to survive through your offspring. That's the rationale for selfish behavior.

Moses: That means that the most rational solution for the group is at odds with the most rational solution for the individual.

Socrates: Exactly, it's a moral dilemma! To whom should you listen - the Angel whispering into one ear telling you to do what helps everyone the most, or the Devil whispering into the other telling you to take care of you and yours before anyone else? It's a tug of war - your Superego doing battle with your Id. Sometimes your selfless impulses win, and sometimes your selfish impulses win. And when other people behave selfishly, you are more inclined to do the same, and vice versa when other people behave selflessly. That's the feedback that drives the oscillations.

Moses: I get what you're saying, but if selfless behavior is not sustainable, then how did my egalitarian simple forager ancestors ever succeed in enforcing the Golden Rule?

Socrates: Because instead of "*Do as to others as you would have done unto yourself*," they started with a slightly abridged version of the Golden Rule: "*Do as to others as you would have done unto yourself, or else you will be punished."* That's where the bitterness factor comes in. All of those cultural status leveling memes designed to "cool the heart" of would-be alphas so they don't step out of line.

Moses: You mean that the sole reason that they cooperated was from fear that they would be punished by the group if they didn't?

Socrates: Curious, isn't it? But that's also the beauty of it! Aggressiveness, bitterness and gossip – all traits with negative connotations that you would not normally think of as admirable, noble or selfless. Yet when mixed together in the right proportions, they created fear-based cooperation that was strong enough to trigger the Egalitarian Transition. Everyone behaved according to their own self-interest, yet the end result was large scale cooperation based on the recognition that it's better to be one among equals than to be dominated by others. And what's more, under those conditions, genuine altruism can then take root.

Moses: It's almost like a bunch of wrongs cancelling each other out to make a right.

Socrates: Typical for emergent behaviors, which are nonlinear and nonintuitive. Seems like magic, but it's not.

Moses: Still, it's hard to wrap your head around how something good comes out of something so seemingly bad. Very perplexing.

Socrates: We like to think that altruistic behavior is good and selfish behavior is bad. But that's making a moral judgment about the intent of the behavior. That's not a practical way for evolutionary biologists to look at altruism and cooperation, since how can you judge the intentions of animals if you can't communicate with them to know what they are thinking? It's also problematic for humans, since intentions underlying human behavior are often multi-layered and ambiguous depending on which layer you choose to emphasize. "The road to hell is paved with good intentions," as they say.

Moses: Then how do you judge when someone is behaving altruistically? Isn't it still altruism if someone tries to help someone else in need, even if it doesn't turn out like they expected? For example, if you jumped into the water to save a drowning person, most people would consider you a hero even if the person still ended up drowning.

Socrates: That kind of altruism is called psychological altruism, since it focuses on the intention of the behavior - a rich subject on its own, but more relevant to psychology and sociology than to evolutionary biology. The type of altruism that concerns evolutionary biologists is called behavioral altruism, which focuses on consequences rather than intentions.

Moses: What kind of consequences?

Socrates: How the behavior affects the fitness of the individual, meaning whether it increases or decreases their chances of producing offspring to carry on their genes. Behavioral altruism is behavior that decreases one's own fitness while increasing the fitness of others - *lose-win* behavior, in other words. Selfish behavior is the converse – it increases one's own fitness while decreasing the fitness of others - *win-lose* behavior.

Moses: What about *win-win* behavior? Isn't that really what egalitarianism is about?

Socrates: Very astute, Moses, *win-win* is indeed the raison d'etre for egalitarianism! It works like this. In a zero sum game in which the amount of resources is fixed, someone must lose for someone else to win, so *win-win* is not possible. The only possible outcomes are *win-lose* (selfish) and *lose-win* (altruistic). Like the females gathering food in egalitarian societies. But if it's a positive sum game and there is a payoff for cooperating, like males cooperating to bring down large game providing meat for everyone, then *win-win* becomes possible. When individuals cooperate so that everyone in the group wins, however, it doesn't, strictly speaking, meet the definition for behavioral altruism, since no one has decreased their fitness by giving up any resources. But it's not purely selfish either, for exactly the same reason. It's really a mixture of selfish and altruistic, 'selfish altruism' if you will. Or if that's too confusing, then 'mutually beneficial'.

Moses: I guess that leaves *lose-lose* behavior as the last remaining possibility. When does that happen?

Socrates: *Lose-lose* behavior decreases the fitness of the group and the individual at the same time, such as spiteful behavior intended to punish someone else by reducing their fitness. It's also a mixture, sometimes called altruistic punishment, or if that's confusing, just 'spite,' like the cultural status leveling mechanisms in egalitarian simple foragers. A modern example is a two-player game called the Ultimatum Game [136] in which one player is given a sum of money, but only gets to keep it if they give a portion to the second player. If the second player is satisfied with their portion, both players get to keep the money, but if the second player is not satisfied, then neither player gets anything. The most rational solution is for the second player to always accept whatever is offered, since both players are better off. But in practice, the second player usually declines anything less than 20-30% because it offends their sense of fairness. That's spiteful *lose-lose* behavior.

Moses: So let me see if I've got this straight. If we take the Public Goods Game as an example, then selfish players are making *win-lose* choices, the rewarders making *lose-win* choices, and the spiteful punishers are making *lose-lose* choices. Who gets to make *win-win* choices?

Socrates: *Win-win* is not really a choice - it's more like a gamble. *Win-win* depends on group behavior – everyone has to cooperate, either spontaneously or because they fear punishment or anticipate reward. And of course, it has to be positive sum game with a payoff, since *win-win* can't happen in a zero sum game.

Moses: In other words, psychologically you can hope for a *win-win* outcome, but it only happens if the others in the community also cooperate. If other individuals decide not to contribute, then you will end up having made a *lose-win* choice.

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[136] **M. Perc, J. Jordan, D. Rand, Z. Wang, S. Boccaletti** and **A. Szolnoki**. Statistical physics of human cooperation. *Phys. Rep.* **687**: 1-51, 2017.

Socrates. Exactly. And that's why *win-win* behavior is so fragile. It depends critically on everyone in the group having a high level of trust in each other. A few selfish free-riders can spoil it for everyone by sowing distrust. Remember in the positive sum Public Goods Game how the selfish player ended up with $44, while everyone else received $24? In that case, everyone was still better off, even though the selfish player became much richer than the others - the classic trickle down scenario. But if just one more player had decided to hedge their bets to protect themselves from the selfish player, then *win-win* goes away. With two selfish players refusing to donate to the public good, the other three selfless players would end up with $18, 10% less than they started with. And it gets worse. With only two players donating to the public good, the selfless players would recover only $12. If only one player donated, they would recover only $6. Does that remind you of anything?

Moses: It sounds like positive feedback. The penalty for behaving selflessly by donating to the public good becomes progressively more severe as more and more players take the option to behave selfishly. Anyone who persists in being selfless under those conditions will soon become bankrupt!

Socrates: Exactly. And not only that, what do you think happens when the payoff for donating to the public good gets smaller, like from 50% to only 10%.

Moses: If all 5 players donated their $20 to the public good, they would each get a return of $22, right? But if one player decided not to donate, the other four would only get back $17.60.

Socrates: Correct. One selfish player, and the other four lose. No trickle down at all. And if two, three and four players refuse to donate to the public good, the selfless players who donate are penalized even more, from $17.60 to $13.20, $8.80 and $4.40.

Moses: So the lesson is that regardless of your principles, it's always a gamble to behave selflessly. And when the going gets tough and the return for donating to the public goods decreases, it becomes even more risky to cooperate. Then your only choice is to protect yourself by behaving selfishly like everyone else.

Socrates: Exactly. Less cooperation reduces the payoff, and lower payoff further reduces the incentive to cooperate. A double whammy. In economics, it's called the Tragedy of the Commons.

Moses: What's that?

Socrates: William articulated the concept in a pamphlet that he published in 1832 [137], to explain why cattle that grazed on common pastures in England were so scrawny and stunted compared to cattle raised on privately-owned pastures.

Moses: What was his explanation?

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[137] **William Forster Lloyd** (1794-1852), the Drummond Professor of Political Economy at Oxford University, was a British economist and amateur mathematician elected to Fellow of the Royal Society in 1834.

Socrates: He pointed out that to maximize profit, each herdsman was economically motivated to own as large a herd as possible. That's fine as long as the total number of cattle doesn't exceed the grazing capacity of the available common land. Once that point is reached, however, adding new cattle threatens the health of everyone's herds due to overgrazing. But that didn't stop the herdsmen. William's explanation was that when one herdsman ignored the risk and added more animals to graze on public common land, that herdsman still realized the full economic gain of the additional animals, but suffered on only part of the cost, since risk of overgrazing was distributed among all of the other herdsman as well. Because the private gain exceeded the commonized loss, self-seeking herdsmen kept adding new animals until the common land was ruined. In contrast, for herds on privately-owned pastures, the owner realized the full gain of adding more animals but also suffered the full cost of overgrazing, and so managed the herd size responsibly without exceeding the grazing capacity.

Moses: Why couldn't herdsmen using commons just agree to limit the total number of cattle?

Socrates: In theory, they could, but in practice, it only takes one selfish herdsman to ruin it for everyone. When one selfish herdsman goes for the competitive advantage by adding cattle to his herd to get the most out of the commons before the resource runs out, the others realize that they will lose out if they don't do the same. One by one, they add cattle to their own herds, and pretty soon it's a stampede and the resource is ruined for everybody.

Moses: Does it still happen today in modern economies? Can't the government step in a regulate the industry?

Socrates: Sometimes it happens before anyone realizes there's even a need for regulation. A classic example was the cod fishing industry in the Grand Banks off the coast of Newfoundland in the North Atlantic. Fishing technology improved in the 1960s and 1970s, allowing much bigger catches each year. After a few years of larger catches, the fisherman were forced to fish over much wider areas to maintain the larger catches. By the 1990s, the cod population had plummeted and the Grand Banks cod fishing industry collapsed. It hasn't recovered since, even after attempts to regulate the industry. Some doubt that it ever will.

Moses: Basically the same outcome as in the Public Goods Game.

Socrates: Except that the Tragedy of the Commons is a negative sum game. If no one cooperates, then overgrazing shrinks the pie and everyone suffers.

Moses: Like cutting off your nose to spite your face.

Socrates: An apt analogy indeed - limited resources coupled to unlimited desires are a formula for ruination!

Moses: How come our simple forager ancestors didn't run into the same problem?

Socrates: The Tragedy of the Commons didn't really apply to them. They didn't have any domesticated animals, crops, industries or wealth, and their only possessions were what they could carry on their back from camp to camp. With no surpluses, sharing food and weapons were essential for everyone's survival, which reinforced the egalitarian culture.

Moses: I see your point. But great apes are simple foragers and they don't exhibit any selfless egalitarian tendencies. So there must be something different about human simple foragers.

Socrates: You are right - that's where the status leveling mechanisms come in. Without a mechanism to punish those who behave selfishly, the inevitable consequence is a breakdown of cooperation. That's why those status leveling mechanisms are so rigorously enforced in egalitarian simple forager bands. They have to know absolutely that they can trust the other members of their band to be honest. A free-rider who talks the talk but doesn't walk the walk when hunting large prey or waging warfare increases the risk of serious injury to everyone else, especially when the going gets tough.

Moses: By your reasoning, then, the Egalitarianism Transition in simple foragers didn't require pure altruism in the *lose-win* sense. It was based instead on spiteful *lose-lose* behavior, by punishing selfish free-riders when they didn't cooperate.

Socrates: Amazing, isn't it, that the Egalitarianism Transition was triggered by such negative qualities – aggressiveness, bitterness, gossip and spite! No genuine altruism was required. As long as cooperation produced a payoff, then a *win-win* outcome emerged.

Moses: Still, it seems pretty dark and depressing if the only motivation to cooperate was fear of punishment.

Socrates: If that were the whole story, it would be. But there is a bright side. If free-riding is severely punished by spiteful punishers to prevent selfish individuals from taking advantage of altruists, then altruistic rewarders can survive. Then *lose-win* altruism stands a chance after all.

Moses: But does that really happen?

Socrates: Psychology experiments have demonstrated it. Take the Dictator Game, for example, in which one player is given a sum of money, and can decide whether to share any of it with a second player. The amount shared varies tremendously, but most times the first player does share a portion, even when the two players never switch roles. So the Dictator Game shows that modern culture does precondition people to behave altruistically even when it's against their immediate self-interest. My guess is that it's a carryover from your egalitarian days - people behave altruistically because they are concerned that if they don't, their reputation will suffer and they will run the risk of being subjected to status leveling measures. Once again, complementary interacting opposites at work!

Moses: How?

Socrates: Altruism is the attractive element holding the group together, selfishness is the repulsive element tending to break it apart, and reward and punishment are the coupling elements that mediate the balance between them. Under the right conditions, if enough people cooperate, then the result will be a *win-win* outcome for everyone. But that's not to say that it isn't a delicate balance. Even among modern humans who are culturally conditioned to cooperate, cooperation is difficult to maintain – it requires constant vigilance to prevent the bullies and free-riders from gaining the upper hand, even in a simple game like the Public Goods Game. The carrot alone is useless without the stick to back it up.

Moses: Yet it seems to explain how egalitarianism could arise despite the *"within groups, selfishness beats altruism"* problem. If the payoff for cooperating exceeds the cost of punishing would-be alphas, then resentment against alpha behavior can be harnessed to keep the bullies and free-riders under control, purely by the threat of punishment.

Socrates: Especially after weapons come into the picture. If a group has to fight a strong bully without weapons, someone has to get close enough to strike the first blow with their bare hands. That's a big risk, since the bully is going to strike back at that individual before the others can pile on and subdue him. But once you have weapons that call kill at a distance, a bully is no match for a group of armed individuals with spears or bows and arrows. Weapons make it much easier for a coalition to punish a bully or free-rider without incurring serious injury to the coalition members.

Moses: Positive feedback again! Resentment against being dominated and gossip drive coalition formation, precipitating to the Egalitarianism Transition. Then weapons make it easier to enforce egalitarianism and lock it in place. And stronger egalitarianism makes for a more cohesive group with a fitness advantage over less cohesive groups.

Socrates: And there's one more key element besides weapons that strengthens egalitarianism.

Moses: What's that?

Socrates: Shame.

Moses: Shame? Now you're going to add shame to aggressiveness, bitterness, gossip and spite as the foundations of human civilization? Why do you always have to focus on our most negative qualities?

Socrates: I'm not being completely negative. Remember, we already let genuine altruism into the picture, as long as the punishers are lurking in the background to protect them. The Golden Rule may start as *"Do unto others as you would have done unto yourself, or you will be punished,"* but in its full glory, it blossoms into: *"Do unto others as you would have done unto yourself, because it's the right thing to do - but if not, you will be punished."*

Moses: I see.

Socrates: Besides, shame is not such a bad thing - it's your conscience talking to you. For other animals living in hierarchical social groups, reward and punishment are very concrete. The agent that rewards or punishes you is a flesh-and-bones physical being like yourself. There is one rule, and it's very simple – *Might makes Right*. But it's very different for egalitarian simple foragers. A single flesh-and-bones alpha individual does not make the rules. The rules have been forged as consensus-based traditions passed down generation to generation through complex language. In other words, the rules are cultural memes with their own independent existence as conceptual entities. They just happen to be enforced collectively by flesh-and-bones living members. That's where shame comes in. Quite a clever adaptation really. You punish yourself psychologically in order to avoid being punished physically by the egalitarian coalition. It saves you the physical punishment and it saves the egalitarian coalition a lot of time and energy. Everyone has selfish thoughts, but shame keeps you from acting upon them so that you don't damage your reputation and standing in the community. It's not possible for other animals because they don't have complex language to agree upon rules of acceptable and unacceptable behavior. Without that, how can they be ashamed of anything?

Moses: In other words, the agreed-upon rules become the foundation for a moral belief system that the community imprints into our brains. It's the angel whispering into our ear, telling us to do the right thing to serve our community!

Socrates: While the devil whispers into your other ear, encouraging you to think only of yourself. That's the human condition in a nutshell - a contest between the angel and the devil, your Superego and your Id, played out on the battlefield of your Ego.

Moses: That must be how religion got started. What better way to impress upon a child the consequences of misbehaving than to threaten him or her with punishment from supernatural forces – "misbehave and you will face the anger of the gods!"

Socrates: Actually, the available evidence suggests that egalitarian simple foragers didn't need moralizing superpowerful gods to make their members behave. Their bands were small enough so that everyone knew what everyone else was doing – life in a fishbowl, as it were! Cultural status leveling memes sufficed to discourage selfish alpha behavior. They had creation myths and spirit gods, of course, but their spirit gods generally didn't concern themselves with human morality. Superpowerful moralizing gods came later, with larger complex hierarchical societies that developed after the Agricultural Revolution led to [138], to allow rulers to better control their subjects.

Moses: All products of our vivid imagination, invented to enforce moral beliefs that serve the community?

Socrates: That's the standard atheist viewpoint, but it's also fully compatible with believing in an impersonal god who doesn't interfere in the workings of the

[138] **Harvey Whitehouse** et al. Complex societies precede moralizing gods throughout world history. *Nature* 568: 226-229, 2019

universe. And if you believe in a personal god who made rules like the Ten Commandments for you to live by, that's fine too. Either way, the end result is the same - it compels people to behave and cooperate for the common good of their community. In the end, all of those beliefs help to overcome the *"Within groups, selfishness beats altruism"* problem, so that *"Altruistic groups (can) beat selfish groups."* At least, that's my commentary on the subject.

Moses: Unfortunately, in modern societies, it seems more and more that selfish impulses get in the way of following the Golden Rule that so powerfully guided our simple forager ancestors.

Socrates: Like I said, it's a work in progress. That's why you need punishers willing to make the *lose-lose* choices, for the times when shame and guilt fail to keep someone's free-riding selfish temptations in line. But it's also why you need rewarders making *lose-win* choices, to encourage people who've done the right thing to keep doing it for the common good.

Moses: It's still a pretty depressing view of humanity - that the only innate qualities that humans are born with are aggressiveness, bitterness, spite, shame, guilt and an ability to learn to use complex language for the less-than-noble purpose of gossiping. Don't you think that we have any inherently noble qualities, like generosity, self-sacrifice, compassion, etc? A God-centered person who believes that humans were created in God's image would be pretty offended by that view. It sounds more like we were created in the image of the Devil!

Socrates: That's the wrong way to look at it, Moses. Humans are born the same as any other species – designed to compete against each other and the rest of the world to ensure that their individual genes are carried into the future by their progeny. That's the "selfish gene", the most fundamental principle of natural selection, hard-wired into each and every one of God's creatures. What's truly astonishing is that despite these innately selfish qualities, your human ancestors were able to rise above them to experience and cherish the noble qualities that you are talking about, like generosity, self-sacrifice and compassion. It's quite extraordinary - a group of aggressive, bitter, spiteful, shameful and gossipy individuals somehow come together and find a way to produce a whole that is so much greater than the sum of the parts! Your noble altruistic qualities are truly an emergent property of the human community! Frankly, to me, that's much more impressive than just being naturally endowed by some creator with innately noble qualities. Instead, you have to earn those noble qualities through a constant struggle with the temptation to behave selfishly rather than selflessly. And you can't do it without the support and encouragement, and sometimes punishment, of your community. It takes a village, as they say. That's why you humans will always be a work in progress.

Moses: I guess when you put it that way, it's not so depressing after all. And maybe even inspirational – only by appreciating and teaching one another can we humans rise above our base instincts to create a fair and just society dedicated to life, liberty, and the pursuit of happiness.

Socrates: Well-said. A heroic struggle to be sure.

Moses: Now that I think about it, there's another line of evidence that supports your view that the 'nobler qualities' are not innate human characteristics.

Socrates: What's that?

Moses: Watching an infant grow into an adult.

Socrates: How so?

Moses: A newborn baby knows instinctively how to eat, sleep and poop, but that's about all - no awareness of anybody else's needs except its own. Completely selfish. I remember becoming a new parent. I had always assumed that you could read a book or watch television at the same time that you were holding a baby. But a baby wants your total attention all the time, and notices immediately when you are distracted! The only time you can get anything else done is when the baby falls asleep.

Socrates: Very true. A newborn baby is aware only of its own immediate needs and demands instant gratification – pure Id, to borrow from Sigmund. Meanwhile, the parents do their best to satisfy the baby's every needs, but also gradually begin to establish limits – negative feedback through punishment and positive feedback through praise and rewards, until the child learns that it can't have everything it wants, that it needs to share and consider the feelings of other members of its community - in other words, to behave selflessly instead of selfishly. As we said, it's not until about four years of age that a child even develops Theory of Mind and is able to realize that others can have different views than their own.

Moses: I guess that if a child doesn't yet have Theory of Mind and can't even imagine that someone else can have different thoughts from their own, then it's easy to understand why it might be hard for them to act selflessly. Like sharing a toy - if they want to play with the toy and can't imagine that another child would not want them to be playing with it, the psychological framework to behave altruistically and give up or share the toy is just not there.

Socrates: But eventually, they get the hang of it, once they learn to speak and develop Theory of Mind. Complex language is critical, since it's much easier to appreciate what someone else is thinking if they can tell you what's on their mind. That's how you teach children the rules of acceptable and unacceptable behavior so that they can develop a conscience – their Superego.

Moses: The Superego that does battle with their Id to bring their selfish impulses under control.

Socrates: And as a child grows, he or she hopefully learns to balance the opposing selfish and selfless choices in managing their Ego. Starting with the parents, siblings, relatives, teachers, and an ever-widening circle of social groups, religious, political, etc., the community defines what's acceptable and what's not. Altruistic behavior emerges from the constraints imposed by the group. It's quite a powerful example of ontogeny recapitulating phylogeny.[139]

Moses: You mean like human embryos going through an early stage of development when they have a tail like a tadpole, which then later disappears?

Socrates: Exactly. Just like you can see the evolutionary history from primitive lifeforms to mammals recapitulated as a human embryo matures, so you can also observe the evolution of primate culture as a human child matures into an adult.

Moses: In other words, the human child behaves selfishly like a nonhuman primate in an alpha hierarchy. But as the child grows, they are socially conditioned, by reward and punishment, to strive for the egalitarian credo, *"Do unto others as you would have done unto yourself,"* like early human simple foragers.

Socrates: You've summarized it perfectly! The parents have no choice but to behave as alphas in a family, because the children are not capable of following the Golden Rule until their minds mature.

Moses: Fascinating. I guess ontogeny does recapitulate phylogeny in more ways than one!

[139] **Ontogeny** refers to the stages of development of the embryo. **Phylogeny** refers to the stages at which different phyla (major categories of animals such as invertebrates, vertebrates, etc) appeared during evolution.

CHAPTER 19: The Devil's Bargain

Moses: One thing still bothers me, though. If what you've sketched is true, then why aren't modern human societies still egalitarian? How did alphas like headmen, chiefs, monarchs, dictators, oligarchs, presidents and prime ministers, etc., gain the upper hand and start bossing everyone else around? If the power of gossip was that strong, what made egalitarianism disappear?

Socrates: Simple - too many cooks spoil the broth. Gossip is great for forming coalitions, but that's just the first step. After everyone has agreed to band together to keep would-be alpha bullies in their place, maintaining a coalition still takes a lot of energy, especially if it's a large coalition. Every member has to have absolute confidence that they can trust everyone else in the coalition. And that trust has to be constantly reaffirmed for the coalition to remain strong and committed. The coalition needs to vigilantly weed out potential free-riders – the ones who talk the talk, but don't walk the walk when the coalition has to take on the risk of confronting a bully.

Moses: Seems like the perfect role for gossip.

Socrates: It is, up to a point. Gossip allows you to compare notes on each other and make judgments about reputation, to determine who is reliable and who can or can't be counted on. But gossip also takes time - so many minutes each day to judge intentions and reaffirm your trust in others. Can you see where I'm heading?

Moses: That limits the practical size that a coalition can reach.

Socrates: Exactly. The larger the coalition, the more challenging it becomes to assess who's trustworthy and who's not. And with so many opinions to take into account, it becomes harder and harder to make communal decisions by consensus.

Moses: So how large is too large?

Socrates: The magic number seems to be between one and two hundred, about one hundred fifty on average. At least that's what Robin's evidence points to [140].

Moses: Who's Robin and why one hundred fifty?

Socrates: Robin's a British anthropologist who noticed a strong correlation between the size of different primates' brains and the average size of their communities. When extrapolated to the size of human brains, the data predicted that humans should be able to comfortably maintain around one hundred fifty stable relationships, defined roughly as the number of people you would not feel embarrassed about joining uninvited for a drink if you happened to bump into them in a bar. Then, when he starting looking, numbers in the one hundred fifty range kept popping up in all kinds of settings. Small businesses, for example - business schools teach that when a business reaches more than two hundred employees, coordination gets too cumbersome and an

[140] **Robin Dunbar, PhD** (b. 1947), a British anthropologist at Oxford University and author of the book *Grooming, Gossip and the Evolution of Language.* See: https://www.youtube.com/watch?v=yXNQLKBjQ

organized hierarchical management structure becomes necessary. Or the army, where the standard company size is one hundred eighty. Even wagon trains in the old west - when Joseph Smith led the Mormon community west to Utah in the 1800s, each wagon train was limited to one hundred fifty in size, since larger ones were too difficult to coordinate. Similarly, when Hutterite communities settled in the Midwest, it was written into the Hutterite charter that they should divide in half once their size reached one hundred fifty. And more recently, social media, in which the average number of Facebooks friends is around one hundred fifty. It's called the Dunbar number, named after Robin.

Moses: I have to say, extrapolating data from non-human primates to humans seems pretty sketchy to me. Last time I checked, other primates reinforce social ties by picking insects out of each other's fur. Humans, on the other hand, use language and gossip. Do you really think that they are even remotely comparable?

Socrates: Actually, Robin came up with a clever explanation for that.

Moses: What's that?

Socrates: Grooming allows primates to express affection and show deference to higher ranking individuals so that physically violent challenges entailing serious injury can be avoided. That's why nonhuman primates devote several hours a day to grooming each other. But they also need adequate time for other vital activities like hunting, gathering, eating, sleeping, mating, and so forth. That limits the amount of time that a primate can afford to spend grooming each day. It's uncommon, for example, for chimpanzee communities to get much larger than fifty individuals. More than fifty encroaches on the time needed for those other activities.

Moses: Interesting, but how is that relevant to humans?

Socrates: When Robin observed humans at social events like cocktail parties, he noticed that when a conversation started between two people, it was common for a third and fourth person to join in. But when a fifth person joined, usually one of the others would leave. It was a pretty consistent observation. He concluded that the optimal maximum group size for gossiping among humans is about four.

Moses: So unlike chimpanzees, who can only groom one other chimpanzee at a time, humans can gossip effectively with three people at a time.

Socrates: Exactly. Hypothetically, that means that if grooming and gossiping require about the same amount of time each day to reinforce social ties, then a human could gossip with three times as many individuals as a chimpanzee could groom. If the upper limit for a chimpanzee community is typically fifty, then a human community would be roughly three times as large, that is, around one hundred fifty.

Moses: Very clever. But what about the new social media technology like Facebook, Instagram and Twitter? Doesn't that allow you to gossip with a lot more than three other people at a time?

Socrates: It's true that you can gossip with a much larger number of people using social media. But remember, the goal of gossip is to know people well enough to trust them. Otherwise, they could be free-riders who are trying to deceive you. That's the real problem – it's not how many people you can gossip with, it's how many people you can know well enough to trust. It's much easier to get away with lying on social media than in a face-to-face conversation.

Moses: So you're implying that if the Dunbar number applied to early humans, pure egalitarianism would break down once the population size exceeded one hundred fifty.

Socrates: Exactly. In fact, most egalitarian simple forager bands are smaller than that. It's not until bands coalesce into tribes with hundreds or thousands of individuals that egalitarianism disappears and leaders like headmen and chiefs start to appear. There have been some exceptions, like the Iroquois Confederation and eighteenth century Montenegrin tribal societies, but for the most part, communities of hundreds, thousands or millions of humans have adopted hierarchies in which designated political leaders make the important decisions. It's just too cumbersome to take everyone's opinion into account when so many opinions are involved.

Moses: So gossip is at the heart of the Egalitarian Transition, but limits the size to which a purely egalitarian community can grow.

Socrates: Precisely. It's not an important limitation for simple forager bands. Their maximum size is constrained by the fact that have to hunt and gather over a large geographical area just to find enough food for everyone. For example, simple forager bands like the Ju/'hoansi usually consist of three or four roving small groups of twenty to thirty, who meet up monthly or so. For a community to grow larger than one hundred fifty individuals requires a dependable source of food concentrated in a small area. Generally, that only happens after humans learn to grow crops and domesticate animals. But it comes at a cost.

Moses: What's that?

Socrates: The Devil's Bargain, as it's been called.

Moses: Devil's Bargain? In reference to what, exactly?

Socrates: For hundreds of thousands of years, humans were nomadic simple foragers living off what they could hunt and gather. They had no domesticated animals or crops. Then, about ten thousand years ago, agriculture came into the picture. That changed everything.

Moses: How could agriculture have been a Devil's Bargain? Surely agriculture was a major milestone for human civilization - finally a dependable source of food for everyone in the community.

Socrates: Be careful what you wish for, as they say. There's also a downside.

Moses: Which is what, exactly?

Socrates: It's not to say that agriculture doesn't offer obvious advantages. Food like grains and vegetables can be grown in excess and stored rather relying on daily foraging, and domesticated livestock can be raised to provide meat on a consistent basis instead depending on the luck of the hunt. The food supply is much more dependable, allowing human communities to grow much larger than one hundred fifty in size.

But the downside is that agriculture is a setup for a vicious cycle. A more reliable food supply leads to an increase in population size until overcrowding saturates the available resources. Overfarming and overgrazing deplete vital resources, requiring longer working hours and more land to maintain crop and herd sizes for an increasing population. Unlike large game hunting, raising livestock and farming can be readily handled by individual families and doesn't require large scale cooperation by the whole community. The more industrious individuals begin to resent sharing the fruits of their labor with less industrious individuals. As nomadic simple foragers transition into the sedentary lifestyle demanded by farming, the concept of private property and private wealth emerge as farmers lay claim to the land, crop and livestock yields that they personally produce. What's left of the egalitarian ethos is progressively eroded as some individuals accumulate more property and wealth than others, creating wealth disparity. As the population expands beyond a few hundred individuals, communal decision-making becomes more and more cumbersome, so political leaders such as head men and chiefs become necessary to get anything accomplished. Warfare between human communities competing over land and other resources results in enslavement of the losers, who are often mistreated as an inferior class and are subjected to poor living conditions and forced labor, even slavery. Close quarter living of humans with animals leads to poor sanitation and the spread of communicable diseases. The less varied diet predisposes to nutritional deficiencies, and makes the community susceptible to famines if they depend largely on a single type of crop. Here's how Edward described the consequences [141]:

> "Ten thousand years ago, the Neolithic revolution began to yield vastly larger amounts of food from cultivated crops and livestock, allowing rapid growth of human populations. But that advance did not change human nature. People simply increased their numbers as fast as the rich new resources allowed. As food inevitably again became the limiting factor, they obeyed the territorial imperative. Their descendants have never changed. At the present time, we are still fundamentally the same as our hunter-gatherer ancestors, but with more food and larger territories. Region by region, recent studies show that populations have approached a limit set by the supply of food and water. And so it has always been for every tribe, except for the brief periods after new lands were discovered and its indigenous inhabitants displaced or killed.
>
> The struggle to control vital resources continues globally, and it is growing worse. The problem arose because humanity failed to seize the great opportunity given it at the dawn of the Neolithic era. It might have then halted population growth below the constraining minimum limit. As a species we did the opposite,

[141] **Edward O. Wilson**, *The Social Conquest of Earth*. Liverwright, 2012. p.76

> however. There was no way for us to foresee the consequences of our initial success. We simply took what was given to us and continued to multiply and consume in blind obedience to instincts inherited from our humbler, more brutally constrained Paleolithic ancestors."

Moses: You make it sound like agriculture was a disaster for the human race!

Socrates: It was a disaster for egalitarianism, that's for sure. But not for human race. Devil's Bargain or not, the Agricultural Revolution marked the final step consolidating your role as the dominant predator on planet earth. It made you into the eusocial superorganisms that you are today [142]!

Moses: What's a eusocial superorganism?

Socrates: It's part of the natural progression of biology - the same basic principle of emergence repeated over and over again at more complex scales, from cells to societies. First you have single cell organisms, like bacteria or amoeba. Then multicellular organisms in which all the cells do the same thing, like slime mold. Then multicellular organisms with specialized cells doing different things, like jellyfish. Then solitary organisms with specialized organs, like flies and frogs. Then social communities of organisms in which all the organisms do the same thing, like locusts or wolves or chimpanzees or human simple foragers. Then, finally, you come to eusocial communities of organisms, in which different individuals have specialized functions, like the ants, termites, bees and wasps with their queens, workers and soldiers. Or post-agricultural humans, with their farmers, laborers, soldiers, politicians, engineers, lawyers, doctors, and so forth. That's what earns a species the distinction of being a eusocial superorganism. It's quite a rare occurrence in evolution – only a few species of insects, birds, and humans have ever achieved it.

Moses: Do really expect me to accept that humans have more in common with insects and birds than chimpanzees?

Socrates: Genetically no, but culturally yes – that is, at least for the last 10,000 years or so since you invented agriculture. By comparison, ants, termites, bees and wasps have been superorganisms for millions of years. Humans are the newcomers.

Moses: Really?

Socrates: Think of it this way. For most social animals, the whole is the sum of the parts. In a chimpanzee community or even a human simple forager band, every individual does pretty much the same thing, aside from gender-related roles. The main reason that they live in social communities is because there's safety in numbers, same as for herds of antelopes, schools of fish or flocks of birds. But in ant, termite, bee, wasp and post-agricultural human societies, specialization and division of labor produce a whole that's much greater than the sum of the parts. Dividing up responsibilities is much more efficient than everyone trying to do everything on their own.

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[142] **Edward O. Wilson**, *The Social Conquest of Earth*, Liverwright, 2012.

Moses: Kind of like an assembly line – having each worker perform a single task on every automobile is much more efficient than having each worker build a separate automobile on his own from start to finish.

Socrates. Exactly, Henry Ford's great insight for the Model T was to copy nature. Imagine if your liver and heart did exactly the same thing - a wasteful duplication of effort and energy. Just like an organism benefits from having specialized organs, communities of eusocial superorganisms benefit from having specialized individuals. And if eusociality confers a survival advantage, then natural selection will reward it. Hence, ants, termites bees and wasps ended up at the top of the invertebrate chain, and you ended up at the top of the vertebrate chain.

Moses: So how did all this come about?

Socrates: Like I said, it's have been a rare occurrence in evolution. In ant, termite, bee and wasp communities, eusociality is mostly hard-wired into their genomes, since all of the individuals, regardless of their specialized function, are genetically related to the same queen. In humans, however, eusociality is culturally-driven, transmitted by memes instead of genes. First, your ancestors had to solve the problem of large scale flexible cooperation by evolving complex language. That was the Cognitive Revolution that led to the Egalitarian Transition. But at that stage, human hunter-gatherers weren't really specialized outside of gender-related differences. The men did most of the hunting and warring while the women concentrated mostly on foraging and child rearing. But once you invented agriculture, things changed. With the Agricultural Revolution, communities became larger and more complex, and work became progressively more specialized. Just like Henry Ford's assembly line, it was more efficient for some individuals to focus on food production, such as farmers and herders, while others specialized in other activities, like food processing, storage and distribution, tool-making, building and construction, commerce and trade, community defense, and so forth. Before long, it was too complicated to coordinate all of the diverse business activities without managers. Accountants became necessary to keep track of the crops, livestock and other resources. That's how written languages and mathematics originally came into being, in order to keep track of production and distribution of goods. As the concept of private property emerged, justice systems and laws became necessary for adjudicating property and personal disputes, along with police to enforce the laws, soldiers to defend the community against invaders, cultural entertainment to reinforce social values by performers, writers, artists and musicians, and so forth. All the trappings of civilization and culture up to the modern age, arranged in a political hierarchy with the working classes at the bottom and an elite ruling class at the top. That's what turned you into the eusocial superorganisms that you are today. And that's how you came to dominate the vertebrate kingdom, just like those insects dominate the invertebrate kingdom.

Moses: Don't you think that was a small price to pay? After all, we're much better off now, especially living in a modern society like the US that prizes life, liberty and pursuit of happiness. It may not be perfect, but it's a lot better than living in caves!

Socrates: Beauty is in the eye of the beholder.

Moses: What's that supposed to mean?

Socrates: I like the way that Yuval put it [143] :

> "Suppose you were given a choice between the following two vacation packages:
>
> Stone Age Package: On day one we will hike for ten hours in a pristine forest, setting camp for the night in a clearing by the river. On day two we will canoe down the river for ten hours, camping on the shores of a small lake. On day three we will learn how to fish in the lake and how to find mushrooms in the nearby woods.
>
> Or:
>
> Modern Proletarian Package: On day one we will work for ten hours in a polluted textile factory, passing the night in a cramped apartment block. On day two we will work for ten hours as cashiers in the local department store, going back to sleep in the same apartment block. On day three we will learn from the native people how to open a bank account and fill out mortgage forms."

Which package would you choose?

Moses: I have to admit, the Stone Age Package sounds more appealing.

Socrates: I thought so.

Moses: On the other hand, suppose that while I was foraging in the woods for mushrooms during my Stone Age vacation, I tripped on a log and broke my ankle. Then I'm sure I'd prefer to be the modern proletarian, with all the advantages of modern medicine to heal me! That has to account for something.

Socrates: Of course, I'm not denying the advantages of modern civilization. But many aspects of the daily life of simple foragers during the Stone Age were healthier. Plenty of exercise, a highly varied nutritious diet unlike the predominantly grain-based high carbohydrate diet in modern societies. That's borne out by comparing the skeletons of nomadic simple foragers to agrarian communities in the past ten thousand years. The simple forager skeletons show much greater bone strength, comparable to those of nonhuman primates [144]. There are fewer diseases when you don't live in close proximity to domesticated animals that facilitate pathogens jumping species, like cowpox in cows jumping to smallpox in humans, or influenza in swine or fowl causing flu in humans.

Moses: Maybe, but life expectancy was also a lot shorter than it is now.

Socrates: True. About a third of children didn't survive to adulthood. But those that did survive childhood typically lived into their 50s. When you consider quality of life, I'm not sure that your modern lives are vastly improved [145].

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[143] **Yuval Harari**, *Homo Deus*. Harper, 2017. p. 175.

[144] **T. Ryan** and **C. N. Shaw**. Gracility of the modern Homo sapiens skeleton is the result of decreased biomechanical loading. *Proc Natl Acad Sci U S A* 112(2): 372-377, 2015.

[145] **James Suzman**. *Affluence Without Abundance: The Disappearing World of the Bushmen.* Bloomsbury USA, 2017.

Moses: What do you mean?

Socrates: Take your average modern worker. Each day, he or she spends eight hours or more working at a repetitive often boring job and sleeps for about eight hours, leaving maybe eight hours of quality time to spend with friends and family on recreational activities each day. So if you live to be seventy-five, about twenty-five years of the total would be quality time.

On the other hand, if you were a simple forager during the Stone Age, you would typically spend less than four hours a day hunting and gathering. With eight hours or so for sleep, that leaves twelve hours a day as quality time. If you lived to be fifty, then overall, about twenty-five years of the total would be quality recreational time, same as the average modern worker. And you'd get to spend that most of that quality time while you were still relatively young! Of course, you wouldn't have television, cell phones or social media to distract yourself with. Instead, you'd have to spend your quality time with your family and friends, using your imagination to entertain each other.

Moses: I can't believe that you think that we were better off as cave dwellers!

Socrates: I'm not saying that one is better than the other, only that they are different. But it does make you wonder whether humanity, despite its success at prolonging lifespan, has dramatically improved the quality of that longer lifespan.

Moses: Do you really believe that?

Socrates: Do you really believe that between overpopulation, climate change, and an economic system that prioritizes profits and economic growth over social justice and preservation of the environment, you are headed towards of world-wide utopia for the human race? It seems more likely to me that you headed towards a global Tragedy of the Commons!

Moses: I thought that the Tragedy of the Commons was about cow pastures in early nineteenth century England.

Socrates: Literally speaking, yes, it is. But if you stretch your imagination and think of the earth and all its resources as the "commons", and the human population consuming the earth's resources as the "grazing cattle", then the issue is the same. How many humans can the earth support before the earth's resources become irreversibly depleted? That's exactly what Garrett [146] pointed out nearly fify years ago - the global relevance of the Tragedy of the Commons. Thanks to the sequential effects of the Cognitive Revolution a few hundred thousand years ago, the Agricultural Revolution ten thousand years ago, the Industrial Revolution two hundred years ago, and now the Information Revolution in the late twentieth century, the world's human population has reached a whopping 7.6 billion people. If you do the math, that means that something

[146] **Garrett Hardin**, The Tragedy of the Commons. *Science*. 162:1243-8, 1968.

like one in fifteen humans ever born since *homo sapiens* first walked on the earth is alive today [147]!

Moses: You can't be serious - one in fifteen humans ever born is alive today? I have only fourteen dead ancestors preceding me?

Socrates: That's the power of exponential growth. It took all of human history up until 1800 for the world's population to reach one billion, but the second billion took only 130 years[148]. Now less than a hundred years later, it's mushroomed to 7.8 billion. Even with the birth rate now declining, the world's population is projected to reach ten billion over the next forty years. Just how many people do you think the planet earth can support? Overpopulation is already driving climate change, pollution, destruction of the rain forests, loss of biodiversity, and the other the vexing challenges of your modern world [149].

Moses: Do you really think that a global Tragedy of the Commons is imminent?

Socrates: It depends. Are you a Prophet, an Ostrich or a Wizard?

Moses: What's that supposed to mean?

Socrates: The Prophets of Doom think that the threshold has already been crossed, and even if radical changes are made to reverse current trends, it may be too late. The Ostriches of Ignorance have their head in the sand and think climate change is a hoax. And the Wizards of Technology think that technology will save us, just like it did at the end of the nineteenth century.

Moses: What happened at the end of the nineteenth century?

Socrates: The Great Horse Manure Crisis of 1894 [150], one of the Wizards' favorite examples of new technology solving vexing problems in the nick of time.

Moses: Are you joking?

Socrates: It may sounds like horse shit, but it's actually true. At that time, big cities like London and New York depended on as many as a hundred thousand horses to transport people and goods throughout the city. With each horse generating twenty five pounds of manure daily, not to mention a quart or so of urine, the projections were that in fifty years, city streets would be buried under nine feet of manure. It was genuinely viewed as a looming crisis for big city dwellers everywhere!

Moses: But technology saved us?

Socrates: Exactly. Out of the blue, the invention of the automobile solved the Great Horse Manure Crisis. Of course, a hundred years later, you now have automobile emissions polluting the environment and promoting climate change – if you wanted to

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[147] See https://www.youtube.com/watch?v=FruPG2M156w
[148] See: http://www.worldometers.info/world-population/#pastfuture
[149] **Elizabeth Kolbert.** *The Sixth Extinction: An Unnatural History*. Holt, 2014.
[150] See https://www.historic-uk.com/HistoryUK/HistoryofBritain/Great-Horse-Manure-Crisis-of-1894/.

honor the past, perhaps you might call the present situation the Great Automobile Manure Crisis of the Twenty-first Century. The Wizards, however, remain undaunted – they have faith that technology will solve the problem in the nick of time by developing clean energy to replace fossil fuels or chemicals that eat pollutants and so forth.

Moses: In the final analysis, though, no matter how advanced technology becomes, it's ultimately limited by the renewable resources available from Mother Earth.

Socrates: Exactly. Without population control, you will always be in danger of the Tragedy of the Commons sooner or later. Too many cattle, not enough renewable pasture.

Moses: Population control is such a touchy issue – so many people consider it an inalienable right to have as many children as they want. And the pro-life movement believing that life is sacred from the moment of conception and that abortion or even contraception are equivalent to murder.

Socrates: It's not unreasonable to consider life sacred from the moment of conception, as long as you also consider life sacred after birth as well.

Moses: What happens when a child's parents can't and society doesn't provide the basic necessities like food, shelter, education and medical care? Which is more humane in that case? To terminate a pregnancy or to bring a child into the world who slowly starves to death or perishes from a completely preventable disease?

Socrates: I agree, it's shameful and heartless to let children suffer when society has the capacity to provide the basic necessities of life to every child world-wide. But at least the latest trends suggest that you may be moving in the right direction.

Moses: How so?

Socrates: Extreme poverty has decreased dramatically in recent years [151]. The number of people subsisting on less than $1.25 per day has decreased from over 50% of the world's population before 1980 to a bit under 10% in 2015. In fact, the United Nations now projects that extreme poverty can be eliminated world-wide by 2030. Pretty impressive, don't you think? And current trends in population growth are also hopeful.

Moses: How so?

Socrates: As developing countries succeed economically and transition from primarily agrarian to industrialized societies, their birth rates have declined dramatically. It may turn out that raising the living standards of poor agrarian developing countries, where the majority of population growth is occurring, is the solution to overpopulation.

Moses: Why do the poorest developing countries have the fastest population growth rates? It seems counterintuitive that starving people would have the most children.

Socrates: Not really. Imagine that you are a farmer living primarily off the crops that you grow yourself in a poor agrarian country. You have to depend on manual labor

[151] See http://www.visualcapitalist.com/chart-end-world-poverty-sight/

since you can't afford fancy tractors or other mechanized agricultural equipment. That's one incentive to have many children, to help you to meet the labor demands of farming and caring for livestock, especially as you get older and can't do as much yourself. And since your country is too poor to provide a social safety net, like social security or retirement plans, ultimately you will have to depend on your children to run the farm in your old age so that you don't starve to death. With limited access to health care in a poor country, effective birth control to limit family size often isn't readily available. Plus the chance of all your children surviving to adulthood is slim. For all of those reasons, a large family provides greater security.

Now contrast that to a city-dwelling factory worker in a developed industrialized country. You work for a weekly salary that has to provide food and housing for your whole family. Children are expensive to raise, required to attend school and are not generally able to contribute economically to the family's welfare until they become adults. Losing your job jeopardizes the health and well-being of everyone in your family. Unlike the poor farmer, when you become disabled or too old to work, you qualify for government-sponsored social security and health care and perhaps a retirement pension. And in a prosperous developed country, better education and availability of health care services make it feasible to control family size more effectively. All those reasons favor a small family.

Moses: Then you don't believe that a global Tragedy of the Commons is inevitable?

Socrates: Not if you collectively put your minds to it. The good news is that as a result of your hard-earned technological achievements, you do now have it in your power to create a literal utopia for all of humanity!

Moses: I suppose that if extreme poverty is now under 10%, that's a step in the right direction.

Socrates: It's a start. However, extreme poverty isn't the only type of poverty. There's also moderate poverty, where people may not be struggling for their day-to-day existence, but they still lack access to quality health care, education and other prerequisites for upward social mobility. The irony is that at this point in your history as a superorganism, you can easily generate enough resources to free all of humanity from extreme and moderate poverty combined.

Moses: Then what's stopping us?

Socrates: The Devil's Bargain - since you've transitioned to eusocial superorganisms, you've largely abandoned the egalitarian one-for-all all-for-one Golden Rule principles that got you started.

Moses: What do you mean?

Socrates: You're not willing to share the abundant fruits of humanity's labor equitably. At last count, you have twenty-six billionaires owning as much wealth as half of the world's population [152], and the wealthiest 1% controlling as much wealth as the other 99%. And it's getting worse each year. In 2018 alone, for example, the wealth of the very richest increased by 12% while that of the poorest half of the world's population decreased by 11%.

Moses: That's pretty astounding, I have to admit. Do you think it's because a large fraction of the world's population lives in authoritarian nations in which elite classes control most of the wealth? I'd bet that if you discounted them, wealth distribution would be more equitable, especially in democratically-governed countries where the people have a voice.

Socrates: Nice try, but unfortunately, that's not the explanation. The US is the wealthiest country in the world and a liberal democracy to boot, yet its track record is one of the worst, with three billionaires now controlling as much wealth as the poorer half of the population [153].

Moses: Even so, the whole point of the American dream is that anyone who is talented and works hard enough can become fabulously rich like one of those three billionaires. That's why the rest of the world thinks of the US as the Land of Opportunity.

Socrates: Once upon a time, but not really anymore. In the US today, the chances of moving up the economic ladder are less than half of what they are in other democracies like Canada or Scandinavia [154].

Moses: Even so, it's not like those US billionaires all came from wealthy families. Most of them built their fortunes on their own initiative.

Socrates: True, but with over three hundred million US citizens, are those three billionaires really fifty million times more deserving of wealth than one hundred fifty million in the poorest half of the population? Is it really fair that some people have more wealth than they can possibly spend in their lifetimes, while others are barely able to get by? Especially when there's more than enough to go around for everyone if it were shared more equitably.

Moses: Is that really true?

Socrates: The figures don't lie. The total private net wealth in the US was almost $100 trillion in 2018. Divided by the US population of 327 million, that's around $300,000 per person, or $1.2 million for a family of four [155]. More than enough to provide the basic necessities of life and more for every citizen! The same is true for the world's population – the total global wealth, about $250 trillion, divided by 7.8 billion people comes out to $32,000 per person. The average family of four would be worth $128,000!

[152] https://www.theguardian.com/business/2019/jan/21/world-26-richest-people-own-as-much-as-poorest-50-per-cent-oxfam-report
[153] https://inequality.org/wp-content/uploads/2017/11/BILLIONAIRE-BONANZA-2017-Embargoed.pdf
[154] https://www.epi.org/publication/usa-lags-peer-countries-mobility/
[155] https://www.brookings.edu/blog/up-front/2019/06/25/six-facts-about-wealth-in-the-united-states/

Moses: But if everyone received the same share of wealth, what would be the incentive to work hard? The dream of becoming fabulously wealthy is what motivates innovators to build new industries that create new jobs that benefit everyone.

Socrates: Yes, the classic theory that rational self-interest and competition guided by the 'invisible hand' of a free market generate economic prosperity for all. Adam [156] and I went round and round on that one.

Moses: But what's wrong with it? It's not like those billionaires did anything illegal to accumulate those fortunes. They followed the same laws as everyone else.

Socrates: True, but just because something is legal doesn't mean that it's fair. Human history is riddled with monarchs and authoritarian leaders who've enacted laws that benefit an elite class at the expense of everyone else.

Moses: Sure, but that's why we don't have monarchs or dictators making the laws here. In a democracy like the US laws are made by elected officials who take an oath to serve the will of the people, not the will of a despot or an elite class.

Socrates: That may be true in theory, but is it really true in practice? When individuals acquire great wealth, they also acquire political power that they use to manipulate the odds in their favor, to ensure that rich get richer, even if it means that the poor get poorer.

Moses: Isn't that what elected political leaders in a democracy are supposed to prevent?

Socrates: If they're doing such a good job, then why is wealth disparity increasing instead of decreasing?

Moses: Good point. But at least it's not as bad as in authoritarian governments, where there are effectively no checks and balances at all on the leaders.

Socrates: You might think so, but you would be misinformed. Ever heard of the Gini index?

Moses: What's that?

Socrates: A commonly-used index used to measure wealth or income disparity, invented in 1912 by Corrado, the Italian statistician and sociologist[157]. The Gini index ranges from zero to one. Zero means that wealth or income is equally distributed

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[156] **Adam Smith** (1723-1790), Scottish economist, philosopher and a pioneer of political economy. His classic work *An Inquiry into the Nature and Causes of the Wealth of Nations* (1776) is considered his magnum opus laying the foundations of classical free market economic theory, developing the concept of division of labor and expounding upon how rational self-interest and competition can lead to economic prosperity, guided by the 'invisible hand' of the market: the unobservable market force that helps the demand and supply of goods in a free market to reach equilibrium automatically.

[157] **Corrado Gini** (1884-1965), the Italian statistician, demographer and sociologist, developed the Gini index as a measure of statistical dispersion intended to represent the income or wealth distribution of a nation's residents. It is one of the most commonly used measurement of inequality.

among all members of the population; one means that a single person controls all of the wealth or income. Can you guess the Gini index for wealth distribution in the US?

Moses: I have no idea.

Socrates: In 2019, it was 0.852 [158].

Moses: That sounds pretty high. What does it actually correspond to?

Socrates: Roughly-speaking, it corresponds to the poorest half of the US population controlling 2% of the wealth, and the top half controlling 98% (Figure 19-1A). Not only that, within the top half, the wealth distribution is very skewed, with the top 10% owning 70%, the top 1% owning 35%, the top 0.1% owning 20% and the top 0.01% owning 11%.[159]

Moses: How does that compare to other countries?

Socrates: Fourth highest in the world. Right now, the only countries with a higher Gini index than the US (0.852) are the Netherlands (0.902), Russia (0.879) and Sweden (0.867). The Western European social democracies range from 0.603-0.828 (Figure 19-1A). China is 0.702, India 0.832 and Japan 0.662.

A

Total Wealth Distribution		
Wealth Percentile	***USA***	***Western Europe***
Bottom 50%	2%	5%
Top 50%	98%	95%
Top 10%	70%	60%
Top 1%	35%	25%
Top 0.1%	20%	-
Top 0.01%	11%	-
Gini Index	0.852	0.603 - 0.828

B

Total Income Distribution		
Income Percentile	***USA***	***Western Europe***
Bottom 50%	20%	25%
Top 50%	80%	75%
Top 10%	35%	35%
Top 1%	20%	10%
Top 0.1%	7-8%	2-4%
Gini Index	0.41-0.47	0.25-0.35

Figure 19-1. Wealth and income distribution in US versus Western Europe during the period 2010-2020. **A**. The percent of wealth controlled by the richest percentage of the population and the Gini index for wealth. **B**. Same for income (both labor + capital).

Moses: Do you mean to tell me that the world's leading democracy has greater wealth disparity than any of the authoritarian oligarchies and dictatorships in the world except for Russia?

Socrates: Yep.

Moses: How about the Gini index worldwide?

Socrates: As you might guess, with twenty-six billionaires

[158] See https://en.wikipedia.org/wiki/List_of_countries_by_distribution_of_wealth#List

[159] **Thomas Piketty.** *Capital in the twenty-first Century*. Harvard University Press, 2014. Table 7.2. See also https://www.economist.com/united-states/2020/05/07/have-the-top-01-of-americans-made-out-like-bandits-since-2000

controlling as much wealth as half of the world's 7.8 billion people, the world Gini index is also quite high, with a value of 0.885.

Moses: And how does that compare to the past?

Socrates: It's higher today than ever, even compared to the ancient world.

Moses: Like how ancient?

Socrates: Like when pharaohs and emperors roamed the earth.

Moses: That's preposterous. How can you even know what the Gini index for wealth was back then?

Socrates: Anthropologists have estimated it from the size of the foundations of houses excavated from the ruins of ancient cities [160].

Moses: What do the foundations of houses have to do with the Gini index?

Socrates: Those scientists found that in the present day world, the distribution of foundation sizes of houses becomes progressively more skewed as the Gini index increases. In other words, wealthy people live in big houses and poor people live in small houses. They used that correlation to estimate the Gini index from 62 archeological sites in Eurasia and the Americas, from about 9,000 BC to the present.

Moses: And what were the results?

Socrates: After the appearance of domesticated crops, the average Gini index was around 0.35. It remained fairly stable in the Americas but progressively rose in the Middle East, China, Europe and Egypt. The highest Gini index in their study was 0.75 in the ancient Egyptian city of Kahun about 2,000 BC during the reign of Pharaoh Mentuhotep III. The second highest value of 0.60 was in ancient Pompeii, around 1 AD during the reign of the Roman Emperor Augustus Caesar. Both are considerably lower than the Gini index for wealth distribution in the US (0.852) and the world (0.885) today.

Moses: So basically wealth disparity is worse today than it's ever been since the dawn of human civilization?

Socrates: It would appear so.

Moses: What about income, then? That's what people actually live on from year-to-year.

Socrates: That's measured by the Gini index for income disparity, defined the same way. Unfortunately, there's no data about income distribution from ancient times, but in modern times, the Gini index for income disparity is lower than the Gini index for wealth.

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[160] **T.A. Kohler** et al. Greater post-Neolithic wealth disparities in Eurasia than in North America and Mesoamerica. *Nature*. 551:619-622, 2017.

Moses: That sounds encouraging. If income is more equitably distributed, then more people can save money and accumulate wealth, which should, in the long run, translate into less wealth disparity, right?

Socrates: You might think so, but according to recent trends, things are going in the opposite direction. In the US, the Gini index for income averaged around 0.36 in the mid-twentieth century, but has been steadily climbed to 0.41-0.47 in the early twenty-first century [161] (Figure 19-1B). Today, that translates to the top 50% receiving 80% of the income, the top 10% receiving 30%, and the top 1% receiving 20%. The top 0.1% that used to receive 2% of all income in the 1960-1980 period now receives 7-8%.[162] In most of Europe, on the other hand, the income Gini index is lower, ranging from 0.25-0.35 without much change since the mid-twentieth century (Figure 19-1B). The top 50% receives 75% of the income, the top 10% receives 35%, the top 1% receives 10% and the top 0.1% receives 2-4%.[163] Similar for India (0.35-0.38) and Japan (0.33-0.38) today. Russia (0.38-0.41) and China (0.39-0.47) are also slightly lower than the US For the whole world, the income Gini index was 0.38 in 2007.

Moses: Okay, but total income and wealth have also increased a lot over the past century, right? Even if the lower classes haven't benefited as much as the wealthy classes, aren't they still better off than they used to be? [164]

Socrates: Ah, the "trickle down" theory that conservatives wax about so rapturously – that when the rich get richer, poor also get a little richer, so it's a *win-win* outcome for everyone.

Moses: Are they right?

Socrates: It depends on your perspective.

Moses: What do you mean?

Socrates: You are correct that the per capita gross domestic product (GDP) of the US has more than doubled since the mid-twentieth century. That means there is more than twice as much total income to go around. When the increase in per

U.S. Population	Real Income Growth	
Quintile	***1947-1979***	***1979-2012***
0-20%	+122%	-12%
20-40%	+101%	-0.1%
40-60%	+113%	+8.4%
60-80%	+116%	+49%
80-100%	+81%	+75%

Figure 19-2. Real income growth for the poorest (0-20%) to wealthiest (80-100%) quintiles of the US population over the periods 1947-1979 and 1979-2012. Note that the real income growth has been negative for the poorest 2 quintiles since 1979.

[161] See https://www.chartbookofeconomicinequality.com/inequality-by-country/usa/ and https://en.wikipedia.org/wiki/List_of_countries_by_income_equality
[162] **Thomas Piketty**. *Capital in the twenty-first Century*. Harvard University Press, 2014. Table 7.3 & 9.5
[163] **Thomas Piketty**. *Capital in the twenty-first Century*. Harvard University Press, 2014. Table 9.6
[164] For example, suppose that the poorest half of the population used to receive 30% of the income in the mid-twentieth century, but now only receive 20% in early twenty-first century. If the total income doubled in the interim, then they would be receiving proportionately less of the total, but in absolute terms, 33% more income than they had before. So even though the richest half of the population gets more proportionately (a 228% increase in their income), the lower classes are still significantly better off.

capita GDP is factored in, the real income growth from 1947-1979 was fairly equitably shared between the working and wealthy classes. So that thirty-two year period was a *win-win* for everyone. But it wasn't really trickle down – it was more like a slight 'trickle up', since the poorest segments saw a bit larger percent increase in real income than the wealthier segments (Figure 19-2)[165].

Things changed, however, in the 1980s when the conservatives came into power during the Reagan era. The conservatives argued that reducing taxes would give consumers more spending power and make businesses more profitable, thereby stimulating robust economic growth and new job creation. Theoretically, by increasing the size of the pie, everybody would win. Growth would offset the loss of tax revenue to the government and new jobs would increase income of the poor as well as the rich.

Moses: And did it work?

Socrates: We'll never really know.

Moses: What's that supposed to mean?

Socrates: Because around the same time as the major tax cuts, the US economy also underwent a major transformation, from a mostly manufacturing economy to a mostly service economy.

Moses: What happened?

Socrates: Economic globalization really started to take off. International trade barriers were lifted, allowing capital and labor to flow more freely so that resources could be allocated to where they were most productive. On the global scale, it worked like a charm. The world's GDP skyrocketed from $10 trillion in 1979 to $75 trillion in 2012 and over $90 trillion in 2020 [166]. Not only that, but extreme poverty, defined as living on less than $1.25 a day, fell from over 50% of the world's population in 1980 to just under 10% by 2015.

Moses: Sounds like a great success!

Socrates: Globally yes, but domestically no. Unfortunately, the outcome for average workers in developed countries like the US wasn't so rosy. During the subsequent 32 year period from 1980-2012, virtually all of the gain in real income went to the wealthiest half of the US population, and most of that to the top 20%. The poorest 40% actually saw their real income decrease (Figure 19-2). So instead of a *win-win* outcome for all US citizens, it turned out to be *win* for the wealthy and a *lose* or *break- even* for everyone else.

Moses: So the trickle down effect worked globally, but not domestically. How is that possible?

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[165] http://scalar.usc.edu/works/growing-apart-a-political-history-of-american-inequality/incomes?path=mind-the-gap

[166] See https://fred.stlouisfed.org/series/MKTGDP1WA646NWDB and https://www.statista.com/statistics/268750/global-gross-domestic-product-gdp/

Socrates: It's a natural consequence of economic globalization. When the US was still primarily a manufacturing economy before 1980, most businesses made their products domestically, which provided a steady flow of good manufacturing jobs to the working classes. The more profitable a business was, the more good jobs it provided to US citizens. In other words, the economic interests of management were aligned with the economic interests of the domestic labor force, the ideal situation for a *win-win* outcome.

But after 1980, that alignment changed [167]. The loosening of global trade and finance restrictions encouraged large domestic US corporations in many sectors of the economy to transition into multi-national corporations. That way, they could register their corporations in foreign countries with lower corporate tax rates, manufacture their products in foreign countries with the cheapest overseas labor, and sell their products to consumers everywhere because of low tariffs. A fool-proof formula for increasing productivity, lowering costs, stimulating economic growth and increasing profits! Except for one small complication.

Moses: What's that?

Socrates: Those manufacturing jobs that used to provide life-time employment and financial security for the average worker in the US disappeared. It was more profitable for multi-national corporations to move those jobs overseas to developing countries where labor is cheaper. Or else to replace them with automation when advances in technology made that possible. In other words, the economic incentives of multi-national corporations were no longer aligned with the national economy and domestic labor force. They were aligned with the global economy and the global labor force instead. That's why even though the US economy boomed in parallel with the global economy, the benefits went almost exclusively to the wealthy US citizens while the lower and middle classes actually lost ground (Figure 19-2).

Moses: And because the US income tax rates had been slashed by nearly half, the wealthy got to keep much more of that income too!

Socrates: Exactly. In the 1950s, the average CEO made twenty times the salary of the average worker. Today it's something like two hundred seventy times that amount [168].

Moses: That's outrageous!

Socrates: Many people think so. However, there is a bright side. Those good manufacturing jobs that were transferred from US to developing countries where labor was cheaper had a very positive impact on their fledgling economies (Figure 19-3). When China adopted capitalist market reforms in the 1980s, the new manufacturing jobs from foreign investment stimulated the creation of a prosperous middle class that hadn't existed before, spearheading China's transition into the world's second largest

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[167] **Dani Rodrik**. Globalization's Wrong Turn and How It Hurt America, *Foreign Affairs*, July/August 201

[168] See https://www.cnbc.com/2018/01/22/heres-how-much-ceo-pay-has-increased-compared-to-yours-over-the-years.html#:~:text=According%20to%20a%20report%20from,high%20as%20in%20previous%20years.

economy today. It's been pretty dramatic. In 1994, 66% of the Chinese population still lived in extreme poverty (less than $1.25 per day). By 2013, that percentage had dropped to 1.9% [169]. As one of the Asian economic miracles, China was a major reason that global extreme poverty decreased from over 50% prior to 1980 to a bit under 10% by 2015. That's truly a massive trickle down effect!

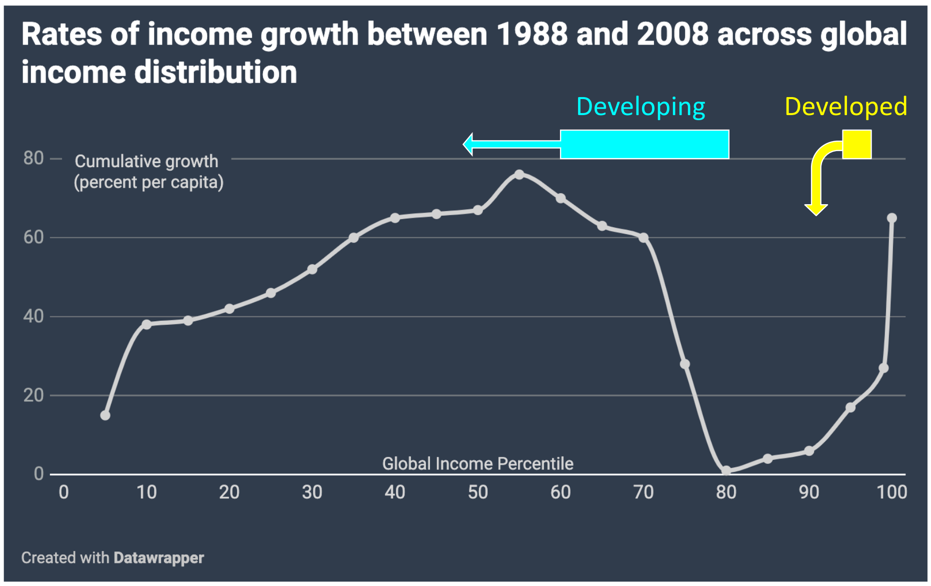

Figure 19-3. Rate of income growth between 1988 and 2008 across global income distribution. The cumulative growth rate (percent per capita) is plotted against the global income percentile. Yellow and cyan boxes indicate the ranges of median income per capita from a selection of developed countries (US, UK, France, Germany, Canada, Japan and South Korea) and a selection of developing countries (China, India, Mexico and Brazil). Note that for the developed countries like the US, individuals earning less than the median (yellow arrow) fall steeply into the percentiles with very low income growth rate indicating the stagnation of the lower and middle classes. In contrast, for the developing countries, individuals below the median (cyan arrow) have maintained high income growth rates promoting the emergence of prosperous middle classes.

Moses: Are you suggesting that those twenty six billionaires who control as much wealth as half of the world's population should give themselves a pat on the back for dramatically reducing extreme poverty globally!

Socrates: I'm sure that they do. Moreover, they would also argue that they had no other choice – their primary obligation is to guarantee the success of their businesses for their shareholders, not to raise the living standards of the US domestic labor force. In a global market, if they hadn't taken advantage of cheaper overseas labor, their products would have become too expensive to remain competitive and their businesses would ultimately fail.

[169] See http://www.visualcapitalist.com/chart-end-world-poverty-sight/

Moses: A convenient excuse. Basically, they rescued extremely poor people in other nations by taking income away from the lower and middle class US citizens. They might have considered contributing some of their own wealth too.

Socrates: I agree. The 'invisible hand' of the global market that enriched them and trickled down to alleviate extreme poverty globally was more like an 'invisible fist' to the lower and middle classes of their fellow US citizens.

Moses: What's most disturbing to me is that the US isn't just the world's wealthiest country – it's also the world's most powerful liberal democracy, a self-proclaimed Land of Opportunity guaranteeing freedom and justice for all. If we are supposed to be setting an example for the rest of the world, how can it be acceptable for wealth and income disparity to be worse in the US than it is even in authoritarian oligarchies? What kind of example is that to set?

Socrates: Personally, I agree with you. However, a nation's influence on the world stage is ultimately derived from its wealth and economic power, not its commitment to social justice. In the global market economy, it's a contest of survival of the economically fittest nation. Democratic or authoritarian, whichever form of society most effectively harnesses its human capital and natural resources to maximize economic growth and accumulation of national wealth will ultimately not only dominate the world stage economically, but politically and militarily as well. Sadly, when the outcome is determined by a nation's economic achievements, commitment to social justice is important only insofar as it boosts those achievements. Money talks, as they say.

CHAPTER 20: When the Market Rules

Moses: What you are really saying is that humanity's priorities are backwards. Instead of fashioning the economy to serve the goals of society, society is being fashioned to serve the goals of the economy.

Socrates: That's a very economical way to put it. Not only that, but as the economy becomes more and more global, the pressure to conform society to the economy becomes greater and greater.

Moses: Why is that?

Socrates: Before economic globalization, nations used to be able to protect their domestic economies by imposing tariffs and restrictions on the flow of capital and labor into and out of their country. However, those protectionist measures ultimately decrease the efficiency of market capitalism by impeding competition. When trade barriers are removed, capital can then flow unrestricted across national boundaries to where it is most needed and can be most efficiently utilized, so that more goods can be produced more cheaply than ever before. As a result, economic globalization has led to unprecedented gains in productivity, with the Gross World Product has increasing from $1 trillion in 1900 to $7 trillion in 1960, to $19 trillion in 1980, to $41 trillion in 2000, and to $90 trillion in 2020.[170] That's nearly a thirteen-fold increase over the past sixty years, compared to a 2.6-fold increase in the world population over the same period. In other words, the productivity of the average worker has increased by a factor of five since 1960. Can you really imagine giving it all up and reverting to pre-1980s isolationism and protectionism, in which more than half of the world's population lived in extreme poverty, compared to less than 10% now? Extreme poverty is now even projected to be eliminated by 2030, all thanks to economic globalization! Do you really think that you can afford to turn back the clock?

Moses: You sound like the CEO of a multi-national corporation. If it's all so good, then why is wealth and income disparity now at an all-time high?

Socrates: Because although the 'invisible hand' of the market capitalism is very effective in promoting economic growth, it's blind to how that newly created wealth is distributed. To reap the benefits of global trade, nations have to give up protectionist tactics and cooperate to reduce trade barriers. That's the reason that Europe's social democracies formed the European Union, and why the US ratified trade agreements like NAFTA, so that capital and labor can flow freely across national borders to where it can be most efficiently utilized to maximize productivity. It's also why the World Bank, Global Trade Organization, and groups like the G7 and G20 were established in the late twentieth century. Global trade is now primarily regulated by those international

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[170] For nominal Gross World Product in constant 1990 dollars: see https://en.wikipedia.org/wiki/Gross_world_product#Historical_and_prehistorical_estimates AND http://statisticstimes.com/economy/gross-world-product.php

organizations, rather than by individual nations. To participate in the global economy nowadays, nations have to waive their right to economic self-determination. If they unilaterally adopt trade restrictions to protect their domestic economy, they face sanctions and other penalties imposed by the global trade organizations. So instead of nations being able to fashion their economy to serve the goals of society, they are forced to fashion their society to serve the global economy.

Moses: In other words, big businesses in developed nations like the US end up outsourcing good middle class jobs overseas to reduce labor costs, and use their political influence to cut taxes, which negatively impacts public funding for social benefits that average citizens depend on, like public education, health care, social security and so forth. The net result in developed nations is that the rich get richer and the poor get poorer.

Socrates: Exactly. Market capitalism is designed to create winners and losers, so that only the strongest and most efficient survive. The market rewards the most productive, and discards the unproductive. It's not about fairness or justice or truth, it's about survival. Just like the selfish genome. If you substitute "number of surviving offspring" in biology with "number of profitable (surviving) businesses," you have the market economy. It's like any other evolving biological network.

Moses: I don't quite follow you.

Socrates: Think of the market economy as a network of businesses striving to survive by being as profitable as possible. Each business is a node, with incoming links from its suppliers and outgoing links to its customers. The network grows as new businesses randomly open up and form new links with other businesses already in the network. New businesses prefer to form links with established businesses that have solid reputations for dependability. Sound familiar - a random, growing network with preferential attachment to already established nodes?

Moses: Aren't those are the factors that end up producing densely-interconnected scale-free small-world networks (Figure 11-1)?

Socrates: Correct - a robust, adaptable and efficient network for matching supply to demand, based on optimizing the creation of wealth. That's the capitalist market economy in a nutshell.

Moses: Like the competition for routes in the airline industry? Didn't you say before that they naturally evolved into a scale-free small-world network?

Socrates: Exactly, a perfect example. The airline industry is a sector of the economy that operates predominantly according to market competition, especially after it was deregulated in 1978 [171]. Different airlines compete with each other for the most profitable routes, and that competition ends up producing a classic small-world scale-

[171] The **Airline Deregulation Act** signed by President Jimmy Carter in 1978 removed federal government control over such areas as fares, routes, and market entry of new airlines.

free network to get you where you want to go as efficiently as possible. There's no central top-down authority dictating which airlines should fly between which cities. The different airline companies just follow their own self-interest. The beauty is that the market's 'invisible hand' empirically works out an efficient solution from the bottom-up, just by letting the airlines compete with each other to match supply to demand based on profitability.

Moses: That sounds a lot like a machine learning algorithm – a network whose links are optimized by minimizing a cost function.

Socrates: Very astute of you, Moses! The market does indeed share many similarities to a machine learning algorithm, if you think of raw materials as the input layer and finished products and services as the output layer. In between is a very complex black box linking the input to the output – but instead of a series of hidden layers, like a deep neural network, the market's black box has more of a parallel architecture, like the genomic learning algorithm (Figure 12-1).

Moses: What do you mean?

Socrates: Instead of hidden layers of nodes stacked one after the other in series, the market consists of interacting modules connected bidirectionally to each other in parallel. Each module is a small world scale-free network of businesses representing a sector of market, and together they produce the intermediate components required for the finished products to be marketed. The links are the transactions between all of those businesses that match supply to demand by minimizing a cost function.

Moses: What is the cost function?

Socrates: The cost-to-price ratio, roughly speaking. Each business tries to minimize its costs from suppliers, and maximize its price to customers - optimized to whatever the market will bear. The smaller the ratio, the greater the profit margin. There is no overarching top-down central command structure that sets prices – the rules are for the most part applied locally, bottom-up, through the nodes of the network.

Moses: How, exactly?

Socrates: Each seller bargains to charge the highest price to the buyer, and each buyer bargains for the lowest price from the seller. Take an automobile company, for example. As buyers, auto makers negotiate the lowest prices from their suppliers to manufacture their automobiles at the lowest cost possible. Then, as sellers, they charge a higher price to their customers to achieve a desired profit margin. Customers, on the other hand, want the best value for their money. If one auto maker sets too high a price compared to its competitors, customers will choose a different brand. That way competition assures that at each stage of the manufacturing process sellers will charge a price reflecting their lowest acceptable profit margin, all the way from the input layer through the intermediate modular layers to the output layer. The local negotiations between the sellers and buyers at each level assure that the prices are reasonable and supply remains well-matched to demand, as long as competition is robust and there are no monopolies powerful enough to fix prices. That, in summary, was Adam's great intuition about how the 'invisible hand' of the market balances rational self-interest and competition to generate economic prosperity, way before anyone knew anything about scale-free networks or machine learning.

Moses: In other words, it's the feedback between buyers and sellers that optimizes prices so that supply matches demand.

Socrates: Exactly, the market is full of feedback loops between sellers and buyers. For example, if there is a shortage of steel, the cost of steel increases and makes the cost of automobiles go up, which reduces the demand for automobiles since fewer customers can afford to buy them. With less demand, fewer automobiles are manufactured. That reduces the demand for steel, so that the supply of steel increases. The glut of steel then causes its price to decline, reducing the price of automobiles, and so forth, to match the demand to the supply. The back and forth of those fluctuations naturally converges to reach the optimal prices for both steel and automobiles. Of course, steel is used for many other purposes besides manufacturing automobiles, and the price of automobiles depends on more than just the price of steel. The number of automobiles sold to customers also has downstream effects on many other industries, such as automobile service and repair, tire manufacturers and the rubber industry, gas stations and the oil industry, the travel industry, etc. So it gets very complicated very quickly, with just too many interdependent variables for a top-down central control mechanism to set prices that coordinate supply-demand effectively.

Moses: It still baffles me how an efficient solution in a very complex system like the economy emerges from applying simple rules locally, without any central coordinating control mechanism.

Socrates: We already mentioned a few examples, remember? Like a flock of birds flying in formation, or the robot walking competition between Ambler and Genghis. Also Google's experience with Google Translate, where after 10 years of frustration with a top-down approach, they switched to a bottom-up deep learning AI approach and had a commercially successful product only 9 months later[172].

Moses: So just by applying the simple rule of adjusting prices to match supply and demand at the local level, you think that capitalism creates an efficient, robust and adaptable market economy without the need for top-down central control?

Socrates: That was Adam's original conjecture. Unfortunately, as history has since proven, when the economy operates purely as a free market, without any central controls, it's inherently unstable.

Moses: Why?

Socrates: Because of the excessive positive feedback.

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[172] *The Great AI Awakening* by **Gideon Lewis-Kraus**, New York Times (December 14, 2006), p.36. https://www.nytimes.com/2016/12/14/magazine/the-great-ai-awakening.html

Moses: How does that work?

Socrates: Remember the three features that have naturally shaped the market into a small world scale-free network of businesses - randomness, growth and preferential attachment?

Moses: Sure.

Socrates: That preferential attachment feature is a form of positive feedback, since it promotes strong businesses getting even stronger. That positive feedback causes the free market to eat away at the very foundations it depends on to produce an efficient, robust, adaptable economy.

Moses: How?

Socrates: The ability of the market to optimize productivity by matching supply to demand depends on robust competition, so that the flow of both capital and labor remains free and unimpeded. But when strong businesses get strong enough to become monopolies, they become powerful enough to restrict the flow of labor and capital to their own advantage. Without competition, they can fix prices arbitrarily and have no need to innovate to make a profit. And they can lower wages to increase profit if there are no competing businesses to lure away their skilled laborers. Then the free market is no longer free.

Moses: Can you prevent it?

Socrates: Of course. To keep the playing field even, you need negative feedback to counterbalance the positive feedback – more Yin, less Yang. That's where government has to step in.

Moses: Government regulation is the answer?

Socrates: As one of your founding fathers [173] succinctly once put it: "If men were angels, Government would be unnecessary." Unfortunately, among capitalists, the honor system isn't sufficient. That's why around the turn of the twentieth century, the US congress enacted anti-trust legislation to break up large monopolies in a number of key industries, like Standard Oil in the petroleum industry.

Moses: Did that solve the positive feedback problem?

Socrates: It helped to address the monopoly issue, but it didn't completely solve the problem because there are other sources of positive feedback that also destabilize capital markets.

Moses: What else?

Socrates: Sectors of the market have a natural tendency to oscillate between boom-and-bust cycles. When they synchronize through positive feedback, they can cause the whole economy to crash. Like the 1929 stock market crash that caused the Great Depression, or the 2008 financial crash that caused the Great Recession.

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[173] **James Madison** (1751-1836), from *The Federalist Papers,* no. 51, 1788.

Moses: How does positive feedback play into those?

Socrates: It works like this. As long as investors are willing to invest their resources into businesses, the market economy booms. Businesses grow and it's a *win-win* outcome for everyone. But when investors get spooked and hold on to their money, businesses can't grow and the positive sum game becomes a zero or negative sum game. *Win-win* becomes *lose-lose,* and everyone suffers as the economy grinds to a halt.

Moses: Why do investors get spooked?

Socrates: The fickleness of human nature.

Moses: What's that supposed to mean?

Socrates: I like to think of it in terms of game theory.[174] When an investor invests money in a stock, they are hoping for a *win-win* outcome, but they fear a *lose-win* or *lose-lose* outcome. If other investors cooperate by investing in the stock, the price goes up and it's a *win-win* for everyone. But if other investors are uncooperative and decline to invest, demand for the stock falls, lowering its price so that the investor loses. That ends up as a *lose-win* outcome. For the individual investor, it's basically a guessing game.

Moses: Even so, as long as the investors make their decisions independently, some stocks will go up and some will go down, and the winners will cancel out the losers. Overall, the stock market and the economy as a whole should be stable. How do disasters like stock market crashes occur then?

Socrates: The problem is that investors don't make decisions independently.

Moses: What do you mean?

Socrates: They rely on traits that they inherited from their simple forager ancestors.

Moses: Which traits?

Socrates: Our old friend - gossip.

Moses: The same gossip that drove the Egalitarian Transition? What does gossip have to do with stock market crashes?

Socrates: The same principle, just a different context. In simple forager bands, there were three factors that drove the Egalitarian Transition: aggressiveness, bitterness and gossip [175]. The alpha hierarchy was stable as long as primates acted independently in competing for the alpha position. The primate with greatest ability to dominate and the most resentment against being dominated ended up as the alpha at the top, and the least aggressive, least bitter primate ended up at the bottom. But when gossip allowed

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174 Nearly a dozen Nobel Prizes in Economics have been awarded for game theory applications to economics.

175 **G. Calmettes** and **J. N. Weiss**. The emergence of egalitarianism in a model of early human societies. *Heliyon* **3**(11): e00451, 2017.

primates to secretly complain to each other and form coalitions that could overpower any individual alpha, the structure suddenly transitioned to egalitarianism. It's Yin and Yang once again - the competition between a push factor, aggressiveness trying to stabilize the alpha hierarchy, and a pull factor, bitterness trying to pull the hierarchy apart. Gossip served as the interaction factor that allowed primates who were bitter about being dominated to form coalitions against the alpha, precipitating the egalitarianism transition. A phase transition, just like a melting ice cube.

Moses: And you're saying that gossip plays a similar role in the stock market?

Socrates: Correct. The push and pull factors in the stock market are hope and fear - the optimistic hope that other investors will cooperate by buying stock to drive the price up, and the pessimistic fear that other investors will decline to cooperate so that the stock price falls. Gossip is the interaction factor that links the two and produces positive feedback between investors, either to reinforce hope or to reinforce fear, as the case may be [176]. Basically, those herding behaviors are what create and then burst stock market bubbles.

Moses: How exactly?

Socrates: Say the stock prices of businesses in some industry start to rise. Some investors notice and buy the stocks. They gossip to their friends or clients about the opportunity to make a nice profit. Their friends and clients seize the opportunity and start buying those stocks too, causing the stock prices to rise further, which makes them a profit and entices more investors to buy those stocks, and so forth. That's how positive feedback through gossip creates a stock bubble. But eventually the stock prices rise beyond a realistic valuation of the businesses. When investors sense that the stocks may be overvalued, they stop investing or begin to sell, causing the stock prices to plateau. They gossip to their friends and clients that the stocks have made their run and it's time to sell. Panicked herding behavior in the reverse direction. The reduced demand causes the stock prices to fall. In response, more investors sell their shares and the stocks crash, bursting the bubble.

Moses: So a shrewd investor buys early when the stock price is low and then sells when the price is still high, before the bubble bursts. But a poor investor buys late after the

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[176] **D. Sornette.** A Complex System View of Why Stock Markets Crash. See http://www.er.ethz.ch/media/essays/why_market_crash.html. "The main concepts that are needed to understand stock markets are imitation, herding, self-organized cooperativity and positive feedbacks, leading to the development of endogenous instabilities. We propose that the true origin of a bubble and of its collapse lies in the unsustainable pace of stock market price growth. As a speculative bubble develops, it becomes more and more unstable and very susceptible to any disturbance. …..Recent academic research in the field of complex systems suggest that the economy as well as stock markets self-organize under the competing influences of positive and negative feedback mechanisms. Positive feedbacks, i.e., self-reinforcement, refer for instance to the fact that, conditioned on the observation that the market has recently moved up (respectively down), this makes it more probable to keep it moving up (respectively down), so that a large cumulative move may ensue. "Positive feedback" is the opposite of "negative feedback," the latter being a concept well-known for instance in population dynamics in the presence of scarce resources."

stock price is already near its maximum, and then sells too late, after the bubble has already burst.

Socrates: Timing is everything. It's easy to see how very wealthy investors can manipulate the market, by buying large quantities of shares in a stock to force the price up and spreading the rumor that the stock is hot and a good time for other investors to buy. That drives the stock price up further, at which point the wealthy investors sell their shares at the inflated price, leaving the small investors to fend for themselves. When you have very wealthy investors, it's hard to police the unscrupulous ones who are so driven to make money that they will resort to dishonest behavior like stock manipulation and insider trading to game the system.

Moses: But stock prices go up and down all the time. As long the ones going down are balanced by the ones going up, the economy as a whole is fine. Some investors lose and others win, even if they do so dishonestly. What causes the whole stock market to crash, like in 1929 or 2008?

Socrates: As long as the stock bubbles in different sectors of the economy are not in synch with each other, the booms and busts in different sectors cancel each other out and the economy as a whole is stable. The problem arises when a bubble occurs in a large sector of the economy that is highly interconnected to other sectors – in other words, a hub node in the network. In that case, a crash in a large sector can markedly depress demand for goods and services in other sectors. When the bubble bursts, it percolates through the whole network. Like the real estate bubble in 2008. When the subprime mortgage crisis collapsed the banking industry, which is so fundamentally connected to everything else in the economy, it had a domino effect that threatened the entire economy. If the government hadn't bailed out the "too big to fail" banks after the 2008 housing crash, the domino effects would have spread throughout the whole economy and might have precipitated a second Great Depression like in 1929.

Moses: So the government had to intervene and come to the rescue to prevent the positive feedback from destroying the economy like in 1929?

Socrates: Exactly. After 1929 stock market crash, the governments in capitalist nations introduced much stronger regulation, i.e. negative feedback control mechanisms to dampen the gossip-driven positive feedback underlying bust-and-boom cycles, as a way to prevent them from growing large enough to precipitate a global crash.

Moses: Like what?

Socrates: Like establishing a central bank to raise the interest rate for borrowing money to discourage investment during a bubble, or lowering the interest rate to stimulate investment when the economy is sluggish. And also levying taxes to fund social welfare programs that protect less fortunate citizens from extreme poverty during economic downturns.

Moses: What went wrong in 2008, then?

Socrates: Loosened government regulations allowed banking industry to offer mortgages to unqualified lenders, feeding a real estate buying frenzy. When real estate bubble burst as unqualified lenders defaulted on their mortgages, even very large multinational banks were threatened with bankruptcy. If the government hadn't loaned them trillions of dollars to bail them out, the whole economy would have crashed and ushered in another disastrous Great Depression like in 1929. Even with the government bail-out, the economy still went through a prolonged severe recession. The most unfair part is that the "too big to fail" banks that caused the crash in the first place by their reckless financial speculation recovered very quickly thanks to the government bail-out. Don't you remember the scandal when many of the bankers who were responsible for precipitating the crash still received their usual annual bonuses following year? [177] The average citizen, on the other hand, suffered from the consequences of unemployment and reduced economic growth for many years afterwards.

Moses: It does seem pretty unfair that the bankers who caused the problem pretty much got away scot-free, while the average blameless citizen suffered the consequences.

Socrates: Like I said, the market optimizes economic growth, not fairness or social justice. Even with government regulation designed to suppress major boom-and-bust cycles from crashing the economy and to prevent monopolies from corroding market performance, there's a third element of positive feedback that virtually guarantees the rich will get richer and the poor will get poorer in a capitalist market economy, unless the government intervenes.

Moses: What's that?

Socrates: The $r > g$ effect.

Moses: What's that supposed to mean?

Socrates: Thomas pointed it out recently [178]. r is the average rate of return on investment. g is the average growth rate. The wealthy fraction of the population that has money to invest will see their wealth grow, on average, at the rate r. The poor fraction of the population with no money to invest, on the other hand, will see their businesses or wages grow, on average, at the rate g. If $r > g$, then the wealth of investors will grow exponentially faster than rest of the population.

Moses: But if the rich are the successful entrepreneurs who are building the industries that create jobs and grow the economy, shouldn't they be rewarded? After all, aren't they are the ones creating the *win-win* outcome for everyone else? If there's no growth, then the economy stagnates and becomes a zero sum game.

Socrates: The problem with that argument is that it's not the hard-working entrepreneurs pouring their hearts and souls into building successful businesses who, on average, receive the greatest rewards.

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[177] See https://abcnews.go.com/Business/story?id=8214818&page=1
[178] **Thomas Pikkety.** *Capital in the twenty-first Century.* Harvard University Press, 2014.

Moses: What do you mean? If not the entrepreneurs, then who?

Socrates: Investors - the ones who lend entrepreneurs the capital they need to build their businesses. Unlike the entrepreneurs, investors can just sit back and watch their wealth accumulate without lifting a figure to produce a valuable product on their own.

Moses: How can that be?

Socrates: Easy - let me illustrate. Say the annual growth rate *g* of the gross domestic product (GDP) is around 2.5%, like it's been in the United States over the past few decades. Suppose that Eddy, an average entrepreneur, has no wealth of his own and borrows $100,000 from investors to start his own business. On average, the value of Eddy's business will grow at the growth rate of the US economy *g,* that is, 2.5% compounded annually. At that rate, 50 years later, when Eddy is ready to retire, his business will be worth $343,711. Less the $100,000 that he originally borrowed to start the business, his net wealth will have grown from zero to $243,711 minus the interest paid on the $100,000 loan. Make sense?

Moses: Seems pretty straightforward.

Socrates: Now compare Eddy to Ivan, an average investor. Ivan inherits $100,000 from his well-to-do parents and deposits it in the investment bank that lent the money to Eddy to start his business. Over the past 90 years, the annual rate of return on investment *r* for the S&P 500 index[179] has averaged 9.8%. That means that Ivan's $100,000 will grow, on average, by 9.8% compounded annually. After 50 years, Ivan's net wealth will have increased more than a hundred-fold to $10,718,080.

Moses: That's a pretty large difference.

Socrates: Exactly. Eddy, our average entrepreneur who worked his butt off for fifty years to produce a product of real value to society, creating new jobs in the process, ends up with less than $243,711 for his efforts. In contrast, Ivan, the average investor, has only to sit on his butt to end up a multi-millionaire worth $10,718,080.

Moses: That seems very unfair.

Socrates: It gets worse. Now imagine that after those fifty years of hard work, Eddy suffers a fatal heart attack and the family business is bequeathed to his equally hard-working son, Eddy Junior. Fifty years later when Eddy Junior is ready to retire, the value of the now one hundred year-old business will have increased to $1,048,728 at 2.5% interest compounded annually. Not bad, right? Eddy Junior is now a millionaire.

Meanwhile, when Ivan dies and bequeaths his $10,718,080 to his son, Ivan Junior will be sipping martinis at his country club while watching his inheritance grow at

[179] See https://www.cnbc.com/2017/06/18/the-sp-500-has-already-met-its-average-return-for-a-full-year.html. **Standard & Poor's**, a company that doles out financial information and analysis, was founded in 1860 by Henry Varnum Poor. The "Composite Index", as the **S&P 500** was first called when it introduced its first stock index in 1923, began tracking a small number of stocks. Three years later in 1926, the Composite Index expanded to ninety stocks and then in 1957 it expanded to its current five hundrd. Technology has allowed the index to be calculated and disseminated in real time. The S&P 500 is widely used as a measure of the general level of stock prices, as it includes both growth stocks and value stocks.

9.8% compounded annually. After fifty years, that comes to $1,148,772,449. So Ivan Junior won't be sipping martinis at his country club for long – he'll be sipping them on his billionaire's yacht!

Moses: That seems wildly unfair, even if it's legal.

Socrates: Well, I've exaggerated a bit. Ivan Junior will still have to pay taxes on his earnings. If the profit from his investments were subject to today's longterm capital gains tax rate of 20%, then his effective return on investment rate would fall from 9.8% to 7.8%, and his net worth would only be $182,757,868. Not quite a billionaire, but still enough for a sizeable yacht, don't you think?

Moses: What if the top tax bracket was over 90%, like in the 1960s?

Socrates: It wouldn't apply to Ivan Junior, since the long term capital gains tax in the 1960s was 25%. That would reduce his effective return on investment from 9.8% to 7.3%. After one hundred years, his wealth would total $144,808,011. Still yacht-worthy.

Moses: Wow. That's pretty eye-opening!

Socrates: It's because the formula for compound interest is exponential [180]. Remember how we calculated that if you were able to fold a sheet of typing paper in half 34 times, its thickness would reach past the moon? That's exponential growth equivalent to a doubling every year, which in economic terms would be equivalent to a 100% annual interest rate. At that interest rate, Ivan's original $100,000 would be worth $250 trillion after only thirty-one years. That's as much wealth as exists in the entire world today! Of course, after those thirty-one years, no one else would have anything left to pay any interest to Ivan, so he would have to live off the principal. A 9.8% interest rate compounded annually is a lot smaller, even after a hundred years, but still adds up quickly, much more quickly than 2.5% compounded annually that Eddy received.

Moses: So the values of *r* and *g* really have powerful consequences on wealth disparity in the long term.

Socrates: Most definitely. Of course, we're talking about averages. The difference between Eddy's and Ivan's accumulated wealth is not guaranteed to be that large. If, instead of being the average entrepreneur, Eddy had started a business like Microsoft, Google or Amazon, with initial growth rates in the triple digits, he would have done much better than an average investor like Ivan. Likewise, if Ivan had invested his inheritance in a pyramid scheme, he might have lost his shirt and never got close to owning a yacht.

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[180] The formula for annual compound interest is: $\mathbf{A = P\,(1 + r/n)^{(nt)}}$ where **A** = the future value of the investment/loan, including interest; **P** = the principal investment amount (the initial deposit or loan amount); **r** = the annual interest rate (decimal); **n** = the number of times that interest is compounded per year; **t** = the number of years the money is invested or borrowed for.

Moses: Over the whole US economy, though, it's pretty clear that the average odds vastly favor the investor over the entrepreneur.

Socrates: And they also favor the investor over the average worker, since wages, on average, track the economic growth rate *g*. It wasn't so bad in the mid-twentieth century when the growth rate in the US averaged 4-6% and the top income tax bracket ranged from 70-90%. But now that the growth rate in the US has fallen to 2-3% and the maximum income tax brackets have been reduced to 35% for personal income and 20% for long term capital gains, the investors have a huge advantage over both entrepreneurs and laborers.

Moses: It's one thing to reward people for their hard work when they build a business that benefits everyone by creating jobs, products and services directly useful to society. It's another thing to reward people just because they are wealthy enough to have money to invest, and can just sit back to watch it grow as a result of someone else's hard work.

Socrates: The message is simple: if you want to become wealthy, it's a two-step process. The first step is to start a successful business or save enough of your wages to accumulate a sum of money to invest, like Eddy did for Eddy Junior. Then if Eddy Junior wanted to play the most favorable odds, he would have sold his father's business and invested the profit to grow at rate *r*, just like Ivan had done fifty years before. Eddy Junior would eventually become as wealthy Ivan had fifty years earlier. And then Eddy Junior's son, Eddy the Third, might have had a shot at becoming a billionaire, just like Ivan Junior. A delay of one generation.

Moses: I see your point. On the other hand, if everyone has the same opportunities to become successful, the system isn't necessarily unfair.

Socrates: True. But if you come from a poor family that can't afford to the necessary educational and training resources required to become successful on your own (like Eddy), and you can't expect any inheritance from your parents (like Ivan could), then you're at a big disadvantage. That's how the cycle of poverty becomes self-perpetuating. Without government programs and oversight to guarantee equal opportunity for its less fortunate citizens, the poor stay poor while the rich get richer and wealth disparity gets worse.

Moses: It seems like we've needed to add a lot of top-down government regulation to the free market to try to keep it's 'invisible hand' functioning without monopolies, catastrophic crashes and worsening wealth and income disparity. But isn't there also a danger of having too much government regulation of the market? As I recall, when governments have tried to run the economy in the past, it hasn't worked out too well. It decimated the economies of the Soviet Union, China and many other communist countries.

Socrates: That's because they overdid it. There's a big difference between a government trying to *replace* a capitalist market versus trying to *regulate* a capitalist market to keep its operating principles intact. The Marxist-Leninists viewed capitalism as the fundamental culprit that had led to exploitation of workers by the elite capitalists. So they threw the baby out with the bath water. They tried to scrap the capitalist market altogether and replace it with a top-down government-run, centrally-planned economy. The government set production quotas and dictated to the economic infrastructure how to match supply and demand to achieve those goals. That was their big mistake. It failed for the same reason Ambler or Google Translate failed when they tried to implement a top-down central control strategy. The market is just too complex for a top-down central control strategy to work. It's a densely interconnected network in which supply and demand fluctuate all the time. Everything affects everything else, just like in a biological network, and it's impossible to anticipate everything that can possibly go wrong. The Soviet and Chinese governments just weren't nimble enough to avoid famines and other calamities, and ended up converting the economy from a positive sum game into a zero sum game. Without *win-win* as a potential outcome, the incentive for cooperative behavior disintegrated into authoritarianism in which managers became the elite class and the workers still got the short end of the stick. The intention to redistribute wealth equitably was noble, but as the expression goes, "the road to hell is paved with good intentions." It's an example of how attempting to fashion the economy to serve the goals of society backfired and turned into a complete disaster.

Moses: Then aren't we caught between the horns of a dilemma? As long as $r > g$, market capitalism will inevitably exacerbate wealth disparity and create an elite wealthy class. On the other hand, if we try to prevent wealth disparity by replacing the market with a top-down centrally planned economy, then the economy doesn't function efficiently and prosperity evaporates. Is there no middle ground?

Socrates: Of course there is. The mistake of the communists was to throw out market capitalism altogether and replace it with a top-down centrally planned economy. In retrospect, they should have done what capitalist nations did when it became clear from the Great Depression that unregulated free market capitalism was an unstable disaster.

Moses: Which was what?

Socrates: Keep the capitalist market, but stabilize it using limited top-down government regulation. That's what the Russian, Chinese and other communist governments had to learn the hard way. But now that they've come around and backed off on central planning overkill, they've adapted very successfully to free enterprise-driven market economies, especially the Chinese. Their government is just as authoritarian as ever, but its recent leaders have been very successful, if somewhat ruthless, at stimulating economic growth. They actually may have an advantage over liberal democracies - pervasive state ownership allows them to subsidize preferred industries, pass laws that require foreign companies to transfer technology to domestic firms if they want to operate in China, and to manipulate currency exchange to their own advantage. That's how extreme poverty fell from two thirds of the population to less than 2 percent in only a few decades and why China is now the world's second largest economy after the

United States. And with less wealth disparity than currently exists in the United States, I might add!

Moses: So what you're saying is that the communist nations needed to back off on central control by the government to make their economies run smoothly, whereas the democracies needed to increase central controls by the government to prevent their economies from crashing. Now both systems have met somewhere near the middle. I guess it makes sense, since no liberal democracies are really pure free-market economies anymore. They've all become social democracies that only differ in how strongly the government regulates the market and how much of a social safety net the government provides to its citizens.

Socrates: Exactly. It's a wide spectrum, with the United States on the more conservative side and Europe on a more liberal side. The US government uses tax revenues to fund social security, welfare and Medicare and Medicaid programs, whereas most European governments also fund universal health care and higher education. The differences are reflected in the tax revenue as a percentage of gross domestic product (GDP), which is around 18% in the United States, but about 40% in European countries [181]. And in the United States, over 50% of tax revenues are spent on defense, compared to <5% in European countries. That means that less than 10% of US tax revenue is available for social welfare programs, compared to nearly 40% in Europe.

Moses: Does that explain why wealth disparity is so much worse in the United States than in most of Europe?

Socrates: Partly. Income taxes and capital gains taxes tie into the $r > g$ formula by decreasing the effective value of r, reducing the advantage of investors over entrepreneurs and workers. In other words, if the annual return on investment r averages 9.8%, a capital gains tax of 20% on an investor's profit effectively reduces r by 20% from 9.8% to 7.8%.

Moses: Then why not just increase the capital gains tax from 20% to 75%? That would reduce r to 2.5%, the same as g. Then $r = g$, so that investors have no statistical advantage over entrepreneurs or workers.

Socrates: Nice try, but remember, the economy is a highly interconnected network. Changing one factor may cause unanticipated rearrangements that can defeat your intended purpose. If capital gains were taxed at such a high rate to reduce r, the lower return would discourage investors from investing. The reduced supply of investment funds would then slow economic growth, causing g to fall. At the same time, the increased demand for investment funds would then increase r. Once again, the end result is $r > g$, but now with much slower economic growth. That's why there's such controversy among economists about how tax rates and government regulation affect economic growth. The goal may be to redistribute wealth more equitably by increasing

[181] See https://en.wikipedia.org/wiki/List_of_countries_by_tax_revenue_to_GDP_ratio

taxes and government spending, but if the result is to slow economic growth substantially, then you've shot yourself in the foot.

Moses: Then is there any way to make a capitalist market function so that a significant portion of the world's population doesn't have to be starving while an elite class has more money than it can possible spend?

Socrates: That's the big question.

Moses: It's ironic, isn't it? What originally set humans apart from other species was their ability to cooperate flexibly with each other for the common good, rather than competing with each other to be the alpha, like non-human primates.

Socrates: Very true. The Egalitarianism Transition was the tipping point that gave humans, despite being slower, weaker and less ferocious than any predator close to their own size, the upper hand over the rest of the animal kingdom. When you were simple foragers, you shared everything and punished would-be alphas who behaved selfishly. You focused your competitive drive against other simple forager bands and other genomes, instead of against each other as individuals.

Moses: Then how did we get into our current situation in which twenty-six alpha billionaires control as much wealth as half of the world's population?

Socrates: Because it's equally true that natural selection is based on survival of the fittest, and humans, like all living organisms, are hard-wired to compete with each other. Once you made the Devil's bargain and had a steady enough food supply to increase the size of your communities beyond a few hundred people, egalitarianism was destined to break down. Free-riders became harder and harder to police and punish, especially after farming and livestock led to the concept of privately-owned property and division of labor. Clever aspiring alpha types manipulated less aggressive and more trusting individuals to acquire a greater share of those resources and political power. That provided the opportunity to stack the odds further in their favor and accumulate even more wealth. That, in a nutshell, is your current predicament.

Moses: An unavoidable consequence of us becoming superorganisms, in other words?

Socrates: I'd put it differently. It's the unavoidable consequence of basing your current economic system on the principles of natural selection and survival of the fittest, like biology does. The market is constantly learning to adapt, by rewarding the most profitable businesses (i.e. the fittest) in order to maximize economic growth (i.e. survival). That creates winners and losers. The winners survive and the losers perish. The market doesn't care about individual businesses, only about the market's survival. Just like genomic learning, where it's not the survival of individuals that matters to nature, but the survival of the species' genome. Individual phenotypes, whether organisms or businesses, are just trial balloons to see which ones are best-adapted to succeed in the present state of the environment. As long as some survive, the genome or market avoids extinction. That, unfortunately, gives an advantage to individuals who compete ruthlessly to advance their own interests.

Moses: How ruthless do you have to be?

Socrates: You don't have to be congenitally ruthless, but it's a slippery slope. Even if nine out of ten business owners have angelic dispositions, it often only takes one non-angel to spoil it for everybody. You can see it in the Public Goods Game. At first everyone cooperates to maximize the payoff. Then one non-angel decides to withhold their donation to the public good in order to end up with a greater share than the others. Pretty soon, all the players are withholding their donations as well, and the positive sum *win-win* outcome spirals towards a zero sum outcome (Figure 17-1). In economics, it's the Tragedy of the Commons that Garrett [182] described:

> "The spoilage process comes in two stages. First, the non-angel gains from his 'competitive advantage' (pursuing his own interest at the expense of others) over the angels. Then, as the once noble angels realize that they are losing out, some of them renounce their angelic behavior. They try to get their share out of the commons before competitors do. In other words, every workable distribution system must meet the challenge of human self-interest. An unmanaged commons in a world of limited material wealth and unlimited desires inevitably ends in ruin."

Now just replace the word "commons" with "market." Even if most business owners in an industry strive to behave like angels, when the consequence of angelic behavior is bankruptcy and personal ruination, the temptation to compromise their noble principles becomes almost irresistible.

Moses: I suppose that the fallen angels don't feel that they really have any choice. It's not only themselves but also their employees' livelihoods that are at risk.

Socrates: True, but the inevitable result is that the industry becomes depleted of angels and enriched in non-angels, especially as an industry reaches its growth limit and the competition becomes more intense. Once it becomes a zero or negative sum game, the only way to win is if someone else loses, like in the Tragedy of the Commons.

Moses: But as long as your industry is still growing and it's a positive sum game, shouldn't it still be possible to stay true to your values without going bankrupt?

Socrates: That's why economic growth is such a high priority for businesses and nations alike. Only when you're growing, either by expanding your current market share or by innovating to create new markets, is it possible to maintain a *win-win* for everyone.

Moses: But shouldn't there be limits to how much wealth the investors and entrepreneurs can acquire, especially when other citizens are struggling to obtain the basic necessities of life?

Socrates: A lot of your fellow citizens believe so. But the wealthy sector tends to look at it in a different light, viewing themselves as the essential engines of prosperity who

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[182] **Garrett Hardin**. See http://www.econlib.org/library/Enc/TragedyoftheCommons.html

create wealth and jobs for everyone else. They believe that as long as the economy is growing thanks to their success, they are creating a *win-win* outcome for everyone, both the rich and the poor.

Moses: You mean the trickle down theory.

Socrates: Indeed - the capitalist's eleventh commandment!

Moses: But I thought you said that there hasn't been any trickle down in the US over the past forty years, ever since the maximum US income tax bracket was slashed below 40% (Figure 19-2)?

Socrates: True. In the mid-twentieth century, real income did increase for all US citizens, both rich and poor. At that time the economic growth rate was robust at 4-5% and income taxes on the wealthy were much higher which curbed increasing wealth disparity. The major tax cuts in the 1980s were meant to stimulate economic growth further, with the hope that everyone would benefit from the trickle down.

Moses: Then why didn't it work?

Socrates: Like we said earlier, it might have, but when economic globalization took off in the 1990s, the playing field changed. As international trade barriers came down and domestic US corporations transitioned into multinational corporations, the previous alignment between corporate management and the domestic labor force in the US became misaligned. With globalization, CEO's of the multinational corporations could boost profits and stimulate economic growth by taking advantage of lower labor costs in developing countries. Great for the CEO's and their shareholders, especially with the much lower income tax rates. And great for alleviating extreme poverty on a global scale. But a disaster for the average US worker, whose economic prosperity depended on those good manufacturing jobs that were now going to workers in developing countries or being replaced by automation.

Moses: It seems very unfair, the wealthiest US citizens enriching themselves by taking income away less fortunate citizens of their own nation. Even if it serves a noble purpose of rescuing extremely poor people in other nations, it's only fair that the wealthy should be contributing some of their own wealth too.

Socrates: It depends on your perspective. Those fortunate citizens who became very wealthy played by the same rules as everyone else to achieve their success, so why shouldn't they be entitled to the wealth that they created? And don't forget, many of them give back to society through philanthropy.

Moses: It's true - some of them give away billions of dollars a year. Like Bill Gates. He's supposedly given away over fifty billion dollars to his philanthropic foundation over the past twenty years [183]. Very admirable.

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[183] **Bill Gates**, founder of Microsoft worth $113 billion in 2018, donated $36 billion from 2000-2018 (average $2 billion per year) to the Bill and Melinda Gates Foundation. See https://en.wikipedia.org/wiki/Bill_%26_Melinda_Gates_Foundation

Socrates: Of course, with a one hundred billion dollar fortune presumably generating a 10% or greater annual return, two billion dollars a year is a minor portion of his annual income, so he's never actually come close to touching the principal. Not to mention the tax breaks that he receives for the donated money, which deprives the government of tax dollars that could otherwise be spent on democratically-decided national priorities rather than the pet projects of a philanthropist, no matter how worthwhile those projects might be.

Moses: It's not a very rosy picture that you're painting. It seems like the US democracy has devolved into a system of patronage run by an elite class of wealthy individuals and special interest groups.

Socrates: It's inevitable in a capitalist market that prizes economic growth above all else. The most productive are rewarded and the least productive go bankrupt. And as long as $r > g$, then wealth disparity will inevitability increase. Complicated, isn't it, trying to maximize prosperity and ensure social justice at the same time? That's why conservatives and liberals have such different opinions about the merits of the Greed is Good trickle down philosophy. But one thing's for sure.

Moses: What's that?

Socrates: In the long run, unlimited economic growth can't continue indefinitely without eventually exhausting the earth's natural resources and/or polluting the environment beyond repair. The only question is how rapidly the human race will reach that point of no return if they continue on the current reckless course.

CHAPTER 21: Democracy

Moses: So the lesson is that if the human race continues to pursue unrestrained economic growth as its top priority, a global Tragedy of the Commons is ultimately inevitable.

Socrates: I'm afraid so. As Garrett [184] so eloquently put it, "A world of limited material wealth and unlimited desires inevitably ends in ruin." It's just a matter of time.

Moses: Where do you think that we've gone so wrong?

Socrates: What do you mean?

Moses: It seems that when humans had nothing but what they could kill, forage or carry on their backs, they treated each other as equals, shared almost everything and lived in harmony with nature. But now, after humans have achieved superorganism status and are swimming in material abundance, the Golden Rule seems to have been replaced by a new mantra: Greed is Good. All driven by an elite wealthy class that has accumulated more political power than anyone else, which they use to protect their already excessive wealth, while one in ten people on the planet struggles just to survive.

Socrates: Rather ironic, isn't it? In your egalitarian simple forager days when you had no formal leaders, the most respected and politically influential were not the wealthiest individuals, but the ones who gave away most of their possessions. Take the Ju/'hoansi [!Kung], for instance. As Richard described them: [185]

> "Egalitarianism is not simply the absence of a headman and other authority figures, but a positive insistence on the essential equality of all people and a refusal to bow to the authority of others, a sentiment expressed in the statement: *'Of course we have headman….each of us is a headman over himself.'* Leaders do exist, but their influence is subtle and indirect. They never order or make demands of others, and their accumulation of material goods is never more, and often much less, than the average accumulation of other households in their camp."

He goes on to comment:

> "a precise blueprint exists for how to behave if one wishes to be chosen – and uncontroversially retained - as leader. Thus the widespread reports of leaders acting in an unassuming way, and of leaders being so generous that they themselves "had nothing," do not necessarily mean that bands are choosing as leaders unaggressive individuals who tend to just naturally give away all of their resources. In this type of small society, in which the ethos is shared so uniformly, politically sensitive leaders know exactly how to comport themselves without creating tension. Appropriate ways to assuage the apprehensions of watchful

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[184] **Garrett Hardin**, The Tragedy of the Commons. *Science*. 162:1243-8, 1968
[185] **Christoper Boehm**. *Hierarchy in the Forest.* Harvard University Press, 1999.

> peers are to never give orders, to be generous to a fault, and to remain emotionally tranquil, particularly with respect to anger as a predictable component of dominance. Basically, one needs to avoid any sign of assertive self-aggrandizement. If otherwise capable individuals are irascible, arrogant, stingy or mean-spirited, and do not manage to control these tendencies, they have little chance of gaining or maintaining the leadership role."

Moses: The tables have completely turned nowadays. *Do unto others as you would have done unto yourself* has taken the back seat.

Socrates: Paradoxical, isn't it, that it was the Golden Rule that launched the Egalitarian Transition beginning your dominion over the rest of the animal kingdom! Without that, you'd still be just another species of great apes foraging for scraps in the wild.

Moses: Maybe we should have remained egalitarian simple foragers, instead of transforming ourselves into the wealth-obsessed superorganisms that we've become today.

Socrates: No point in crying over spilt milk! Once you accepted the Devil's Bargain and launched yourselves into the Agricultural Revolution, egalitarianism was doomed by your ever-increasing numbers. There's no turning back to the simple forager lifestyle now.

Moses: If that's the case, then is there really any hope of improving our current situation, or are we just stuck with it?

Socrates: Just because you gave up egalitarianism doesn't mean that you had to give up the Golden Rule! If you really want to create a fairer world, with justice and equal opportunity for all, dedicated to life, liberty and pursuit of happiness, and so forth, the path is simple…….just figure out how to incorporate the Golden Rule back into modern society!

Moses: How did our egalitarian ancestors manage it? Maybe we can learn from them.

Socrates: A good thought, but remember, your egalitarian simple forager ancestors only applied the Golden Rule to members within their own band. They felt no obligation to treat outsiders the same way. In fact, the homicide rate was over 10 times greater than in modern societies because of warring among hostile bands fighting over common natural resources. In those days, you weren't any less tribal than you are now. You just had less sophisticated weapons to kill each other with.

Moses: That doesn't sound very encouraging.

Socrates: Don't be discouraged - where there's a will, there's always a way! It may be true that egalitarian shared decision-making becomes unwieldy once human communities exceed one hundred fifty or so people, such that political power inevitably ends up being concentrated in the hands of an elite. And it may also be true that once an elite class gains power, the temptation to use it to acquire more power and more wealth is irresistible - *absolute power corrupts absolutely*, as they say. But the solution is obvious.

Moses: What is it, then?

Socrates: Find a way to hold your political leaders accountable, so that they have to listen to the people and use their power for the common good.

Moses: Democracy, in other words?

Socrates: Your best hope, if you can perfect it. When leaders are elected by popular vote for a specified term, they can be removed from office if they fail to satisfy their constituents. That way, every citizen has a say in how society operates. There's another advantage too. Since you spent all but the last ten thousand years of your existence on earth as egalitarian simple foragers in which everyone's opinion was taken into account, natural selection has honed your ability to make better communal decisions than individual decisions. That means the Wisdom of Crowds phenomenon from egalitarianism should naturally carry over to democracy, assuming that the democratic process is fair and the key criteria for the Wisdom of Crowds – *decentralization, diversity, independence,* and *aggregation* – are met.

Moses: In other words, democratically elected leaders whose decisions represent popular consensus should make better, more well-reasoned decisions, compared to monarchs, autocrats or politicians controlled by wealthy special interest groups whose unilateral decisions are flawed by confirmation bias.

Socrates: Exactly.

Moses: That all sounds great in theory. But we already have democracies – the United States is one of the world's leading liberal democracies and the most powerful and wealthy nation on earth. Yet wealth disparity is worse now than when kings and emperors ruled the world. If democracy is really the answer, then why haven't we made more progress?

Socrates: That's not democracy's fault. That's American democracy's fault.

Moses: What do you mean?

Socrates: Need I remind you that your nation didn't get off to the strongest start?

Moses: Why do you say that?

Socrates: Take your Declaration of Independence, for instance – *"We hold these truths to be self-evident, that all men are created equal, that they are endowed by their Creator with certain unalienable Rights, that among these are life, liberty and the pursuit of happiness."*

Moses: How can you argue with that?

Socrates: As a lofty poetic sentiment, I can't. But it's pretty hard to make the case that your Founding Fathers truly believed it.

Moses: How can you say that? Our Founding Fathers are considered to be some of the most visionary individuals who ever lived!

Socrates: I say it because I was there when Thomas penned those very words and the other Founding Fathers endorsed it [186].

Moses: You were there? Really?

Socrates: Of course. Do you think I would have missed such a key event in human history?

Moses: Apparently not. Tell me about it.

Socrates: We had a big argument, starting right after the word *self-evident.*

Moses: You mean with the *all men are created **e**qual* part?

Socrates: Exactly. When I first read it, I gave Thomas the benefit of the doubt, and assumed that he was using the word *men* in its broadest possible sense, referring to all human beings, men and woman alike. Boy, was I wrong! I argued with him and the other Founding Fathers until I was blue in the face. They absolutely refused to replace *all men are created equal* with *all humans are created equal.*

Moses: Why?

Socrates: Because they knew that if they won their War of Independence, their next task would be to come up with a constitution for their new nation. And if *all humans are created equal* and have inalienable rights to *life, liberty and the pursuit of happiness*, then it seems pretty inalienable that all *humans* should have a vote in how their new nation operates.

Moses: And they didn't like that idea?

Socrates: Hardly. Just look at how your Founding Fathers punted on the voting rights issue once they'd won their War of Independence. At the Constitutional Convention, they pretty much swept it under the carpet and left it to the Thirteen States to decide who could vote or who couldn't. Call it political expediency if you want, but they all knew how that would turn out.

Moses: Which was?

Socrates: That only white property-owning adult men would end up having the right to vote. Actually, that's not completely correct - New Jersey did initially give white women with property the right to vote, but repealed it within the next twenty years. Other than that small exception, all women from the other twelve states, white men without property, non-white men with or without property, and men and women slaves who were property were denied the right to vote [187]. Overall, only about 6% of the adult population ended up being eligible to vote.

[186] **The Declaration of Independence** composed at the Second Continental Congress in Philadelphia, Pennsylvania in 1776 was first drafted by Thomas Jefferson and then edited by a committee consisting of himself, John Adams, Benjamin Franklin, Roger Sherman and Robert Livingston, followed by the whole congress.
[187] See https://en.wikipedia.org/wiki/Voting_rights_in_the_United_States#Background."

Moses: Not exactly an inclusive democracy! But better than hereditary kings and titled aristocrats calling the shots, I'd say.

Socrates: Marginally. It was still a small elite minority holding all the power. And to top it off, slavery remained legal! How is that consistent with all men being created equal and endowed with unalienable rights?

Moses: I have to admit, that is a disconnect has always puzzled me.

Socrates: Very short-sighted of the Founding Fathers, if you ask me. Especially Thomas – now he has to live forever with a legacy as the Father of American Democracy and a slaveowner at the same time!

Moses: Why do you suppose that the Founding Fathers were so dismissive of anyone who wasn't a white man with property?

Socrates: Do you remember what triggered the American Revolution?

Moses: Sure. Taxation without representation. It culminated in the Boston Tea Party [188] - the protest over the Tea Act passed by the British parliament. The American colonists argued that it violated their rights as Englishmen to be taxed by a British parliament thousands of miles away in which they had no representation.

Socrates: Exactly. Despite all of the lofty rhetoric, the *life, liberty and pursuit of happiness* that concerned them had to do with economic freedom, not universal human freedom. Perfectly sensible from their perspective.

Moses: Why?

Socrates: Because it was white men with property who paid the taxes. Why would they give the other 94% of the population a right to vote on issues that affected their property? Especially when they didn't really trust women or the uneducated masses to make wise political decisions. That, in short, was how your American democracy began.

Moses: But at least it wasn't a hereditary aristocracy. You could start out poor without any property, but if you worked hard and were successful enough to acquire property, you were admitted into the political power structure.

Socrates: True, it was a step in the right direction. Compared to Britain at the time, for instance, the right to vote was also restricted to property-owning men who made up about 3% of the total population [189]. Your Founding Fathers doubled it to 6% - an impressive 100% increase. But still a far cry from universal suffrage!

Moses: Sure, but it was a start, and eventually those inequities in voting rights were corrected by constitutional amendments. The property-ownership requirement was dropped, slaves were freed, and non-whites and women were given the right to vote. Now all citizens, regardless of creed or color or religion, have a legal right to vote!

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[188] See https://en.wikipedia.org/wiki/Boston_Tea_Party.
[189] See http://www.nationalarchives.gov.uk/pathways/citizenship/struggle_democracy/getting_vote.htm

Socrates: Highly commendable steps, I agree. You've made a lot of progress over the past few centuries. That's what makes it all the more puzzling.

Moses: What's all the more puzzling?

Socrates: That the average US citizen seems to be satisfied with the top half of population controlling 98% of the wealth, not to mention just three citizens controlling as much wealth as half of the entire population.

Moses: Why do you assume that?

Socrates: How can I not? In a democracy, citizens have the power to change what they think is unfair. All they have to do is exercise their vote. And since they haven't, what are we supposed to conclude other than the status quo suits them? Only 60% or so even bother to vote in your national elections, and fewer in state and local elections. If they are so unhappy about increasing wealth disparity, why haven't they voted to change it?

Moses: It's not quite that simple. Citizens don't get to vote directly on issues like wealth and income disparity. Or other major issues either, like universal health care, free higher education, protecting the environment, gun control, abortion or whether taxes should go up or down. They only get to vote for candidates who advocate for or against those issues. It's the candidate's responsibility, once elected, to work together with other elected politicians to make good on what they promised to the voters.

Socrates: So ultimately, it depends on the elected candidates being accountable to the voters who elected them.

Moses: Exactly.

Socrates: And are they? Or let me put it this way – if they are, and a majority of citizens believe that wealth disparity has gotten out of hand, then how did wealth disparity get so out of hand?

Moses: Good point, I can't argue with you there.

Socrates: Where's the problem, then? Why doesn't your democracy reflect the will of the people?

Moses: Apathy, I suppose. You can't really blame the voting public for feeling frustrated these days. Since the 1980s, wealth and income disparity have continued to increase regardless of whether Republicans or Democrats have been in power. Their vote doesn't really seem to matter much. That's why in the last presidential election, they voted a disingenuous demagogue into office who claimed that he was going to "drain the swamp in Washington" and "put America first." An act of pure desperation by voters to try something – anything – new!

Socrates: And why do you think that the voting public has become so disillusioned?

Moses: Because they feel betrayed by both political parties. Politicians these days seem to be more beholden to wealthy special interest groups than to the voters who elected them.

Socrates: How? Is bribery and corruption so rampant?

Moses: Actually, wealthy special interest groups do it for the most part without breaking the law. They hire lobbyists to influence legislation. They overwhelm the media with biased advertisements to sway public opinion - especially since 1987 after the Fairness Doctrine requiring television and radio stations to present both sides of an issue was revoked. Nowadays special interest groups have bought controlling interests in major mass media outlets that push outright propaganda supporting their political agendas. And recently, they've managed to get the laws on campaign financing changed to their advantage.

Socrates: How so?

Moses: There used to be strict limits on how much money wealthy individuals, corporations or other special interest groups could contribute to so-called Political Action Committees (PACs), the organizations that raise funds for the campaigns of political candidate and parties. But all that changed in 2010 when so-called Super PACs were declared legal [190]. Wealthy individuals, corporations or other special interest groups can now legally donate unlimited funds to a Super PAC supporting their favorite candidate or party, as long as the money is spent directly by the Super PAC, rather than by the candidate's or party's campaign organization. That means candidates have little choice but to seek support from Super PACs funded by wealthy special interest groups if they hope to get elected these days, given how expensive campaigning has become.

Socrates: So how much of the political contributions come from these Super PACs?

Moses: I read that in the 2012 presidential elections, the top hundred individual Super PACs accounted for more than 80% of total contributions, but represented only 3.7% of all political contributors [191]. That sends a pretty powerful message to candidates that they'd better not disappoint that 3.7% of wealthy donors and special interest groups behind the Super PACs that got them elected if they ever hope to get re-elected.

Socrates: In other words, even though a candidate still has to receive a majority of votes to get elected to office, in reality the voting public only gets to choose between candidates that have been pre-anointed by wealthy special interest groups who fund their Super PACs.

Moses: Regrettably, that's the current state of affairs. It's an insidious process that progressively corrupts the fairness of democracy. Once laws like that get passed, they

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[190] PACs previously were allowed to donate a maximum of $5,000 to an individual candidate or $15,000 to a political party. However, in 2010 the *Citizens United* and *Speechnow.org* judicial decisions made SuperPACs possible, in which PACs that did not make contributions directly to candidates, parties, or other PACs could accept unlimited contributions from individuals, unions, and corporations for the purpose of making independent expenditures.

[191] See https://en.wikipedia.org/wiki/Political_action_committee#Super_PACs

are very hard to repeal, since the politicians who depended on SuperPACs to get elected have a vested interest in *not* repealing the very laws that got them elected.

Socrates: Does it surprise you?

Moses: Not really. The wealthy and powerful have always believed that they know what's best for people without wealth or power. As you pointed out, that's how our nation began – property-owning white men restricting voting rights to property-owning white men.

Socrates: I'm sure that it made perfect sense to them - if the goal is to make a nation rich and powerful, then who better to lead the charge than wealthy individuals with a proven track record of accumulating wealth and power?

Moses: And hope that the prosperity trickles down to everyone else, you mean.

Socrates: Exactly. In game theory parlance, they consider themselves as the selfish altruists who are striving to create a *win-win* outcome for everyone. And it is undeniable that without economic prosperity, the economy becomes a zero sum game in which the possibility of a *win-win* outcome for everyone disappears. That's the time-honored justification for why Greed is Good, the essence of the trickle down philosophy.

Moses: But just because economic prosperity is increasing overall doesn't guarantee a *win-win* for everyone. As you pointed out, the poorest two quintiles of the US population haven't been winning since the 1980s (Figure 19-2). Now they're in the *lose-win* category, seeing their real income decrease as good jobs have moved overseas or been replaced by automation, at the same time that tax cuts to the wealthy are further enriching the rich.

Socrates: Yet at the same time, extreme poverty has decreased substantially in the rest of the world, as a direct result of those prosperous business leaders in developed countries like the US moving good manufacturing jobs to developing countries where labor is much cheaper.

Moses: Whose side are you on, anyway?

Socrates: I'm just looking at it from both sides. If you are the CEO of a prosperous multinational corporation who's increased your company's profits by moving good manufacturing jobs overseas, should you castigate yourself for having advanced your own selfish interests at the expense of the fellow citizens of your nation, very few of whom actually fall into the extreme poverty category? Or should you congratulate yourself for contributing to an overall *win-win* for humanity on the global scale by reducing extreme poverty and helping the most desperate people on the planet?

Moses: Still, you'd think that they'd give a bit more priority to the welfare of their own fellow citizens.

Socrates: I'm sure that they would if they thought they could. But it's easy for them to convince themselves that they don't really have a choice – that if they don't move jobs overseas to reduce labor costs and prices of their products, or register their company in foreign countries with low corporate tax rates, or use their lobbying power to lower US tax rates, they risk becoming noncompetitive and going bankrupt. If everyone does the same, then economic growth stagnates. Then it would turn into a *lose-lose* outcome for everyone, both globally and nationally.

Moses: Do you really believe that? Does wealth disparity in the US have to increase in order for global wealth disparity to decrease?

Socrates: Of course not.

Moses: Then how would you fix it?

Socrates: If the majority of US citizens really want to fix it, it's simple - use their voting power to prevent wealthy special interest groups from stacking the economic odds in their own favor without regard to the impact on the average US citizen.

Moses: How, if politicians are beholden to special interest groups?

Socrates: Look, the problem isn't that US politicians have suddenly become beholden to wealthy special interest groups. That's been going on from the very start when white property-owning men restricted voting rights to white property-owning men. But in the past, the interests of wealthy special interest groups have been more closely aligned with the interests of the average citizen. Most businesses manufactured their products domestically, and the more successful they were, the more good middle class manufacturing jobs they created and the more corporate taxes they paid domestically. In other words, trickle down actually used to work. A *win-win* for everyone.

Moses: But you're claiming that economic globalization has changed all that?

Socrates: Exactly. When international trade barriers came down, those large US corporations realized that they could grow faster and increase profits by transforming themselves into multinational corporations. If profits will go up, it's in their interest to ship job overseas where labor is cheaper, regardless of the impact on the US labor force. If profits will go up, it's in their interest to avoid US corporate taxes by registering their companies in nations with much lower corporate income taxes, and to lobby the US government to cut US corporate tax rates. If it will increase their personal wealth and fuel economic growth by stimulating spending, it's in their interest to lobby the US government to cut individual income tax rates. Meanwhile, the loss of tax revenues deprives the US government of vital resources needed to fund infrastructure, education, healthcare and other social programs that become ever more essential as wealth disparity increases. It also limits the ability of the federal government to fund scientific research essential for developing cutting edge new technologies that US corporations can exploit to maintain their edge in innovation in the global market. The end result is that US economic policies are aligned with the global economy, but misaligned with the domestic economy as far as the welfare of average citizens is concerned. Multinational corporations have used their political influence to advance economic policies that serve their global corporate goals, regardless of the negative consequences to average citizens of their own nation. Domestic trickle down has evaporated, and income and wealth disparity are now at an all-time high.

Moses: How can they be so callous about the welfare of the average citizen in their own nation?

Socrates: They tend to take the global view is that they are using their political influence to enhance global economic productivity for the benefit of all humanity. Remember, as a result of economic globalization, the Gross World Product has increased from $7 trillion in 1960 to a projected $90 trillion in 2020 [192]. Can you really imagine reverting to isolationism and protectionism, in which more than half of the world's population lived in extreme poverty, compared to less than 10% now? Wouldn't that be even more callous?

Moses: I'm not advocating turning back the clock. But is it really fair to place the burden of curing extreme poverty exclusively on the shoulders of the middle and lower classes in developed countries? Shouldn't the wealthy classes who've benefited the most by far from economic globalization contribute a fair share of their personal wealth too?

Socrates: Like I said, the United States is a democracy. All the people have to do is vote to change what they don't like.

Moses: That may be true in theory, but right now it's seems as though the average US citizen is being duped. The traditional political parties and candidates have failed them, and, as result, they've become increasingly disillusioned and angry.

Socrates: You are right. The United States has become as a less-than-ideal form of democracy, and the average citizen knows it. In my opinion, that's the real reason so many of them their backs on traditional political candidates and allowed a populist demagogue to highjack the Republican party in the 2016 elections. After he became president, he behaved more like an autocrat than a traditional president. That's the real danger when democracy fails to deliver - authoritarianism gains an advantage.

Moses: Hard to believe that could happen in a country like the United States.

Socrates: Not just the United States - it's happening in developed nations around the world. Look at all of the turmoil in the European Union, for example. Nationalism on the rise, overtly racist and xenophobic political parties on the upswing. All related to the widespread unrest caused by economic globalism robbing average citizens in developed nations of their ability to improve their lives for themselves and their families. It raises a troubling question about the future of liberal democracies.

Moses: What's that?

[192] Nominal Gross World Product in constant 1990 dollars: see http://statisticstimes.com/economy/gross-world-product.php

Socrates: The common assumption that liberal democracies are inherently a better fit for market capitalism than authoritarian governments because individual freedom of expression translates more effectively into economic innovation.

Moses: Do you really think authoritarianism stifles innovation?

Socrates: Not in the short term. Clever authoritarian leaders, like Xi in China, have become quite adept at manipulating capital markets to their own advantage. Look at how well China has done after abandoning a centrally planned economy in favor of a regulated market economy. The Chinese government is just as authoritarian as ever, but its recent leadership under Xi has been very successful, if somewhat ruthless, at stimulating economic growth at previously unheard of rates. It's an advantage for authoritarian leaders to be able to unilaterally set cohesive national economic priorities and manipulate currency and international trade to their benefit. That's how extreme poverty fell from two thirds of the population to less than two percent in only a few decades and why China is now the world's second largest economy after the United States. And with less wealth disparity currently than the United States, I might add.

Moses: Less wealth disparity maybe, but much less individual freedom than the United States – that's a big price to pay.

Socrates: Believe me, I am hardly advocating for authoritarian governments, just pointing out that some of them have figured out how to manipulate market capitalism to their own advantage quite effectively.

Moses: Better than democratic governments like the United States?

Socrates: It's a very interesting question. In the age of the global economy, is market capitalism more effective at generating prosperity for a nation whose economic policies are driven by a liberal democratic government like the United States, or by an illiberal authoritarian government like China?

Moses: And what do you think?

Socrates: I'd say that it's an open question right now. When authoritarian governments play their cards right, like the Chinese have been doing, they may have the advantage right now.

Moses: Why?

Socrates: Because while the CEOs of multinational corporations are using their political influence to promote the global economy over the domestic economy, powerful authoritarian leaders like Xi in China [193] are doing the opposite – manipulating the global economy to serve their domestic economy, in order to enhance their economic, political and military standing among nations.

Moses: How, exactly?

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[193] **Xi Jinping** (b. 1953) is General Secretary of the Communist Party of China, President of the People's Republic of China, and chairman of the Central Military Commission.

Socrates: By adopting government-sponsored economic policies that subsidize exports by key domestic industries and restrict imports from foreign competitors, by stealing intellectual property by requiring foreign companies to transfer their technology to domestic firms if they want to operate in China, and by manipulating currency exchange to maintain favorable trade balances with other nations. Because of their concentrated political power, the authoritarian leaders can set cohesive targeted economic policies that benefit their nation directly.

Moses: Can you give me an example?

Socrates: Sure. Take the energy industry. By subsidizing the development and mass production of solar and wind power technology, China is now the world leader in this area. It's been good for China and good for climate change at the same time. Contrast that to the United States in which the fossilized CEOs of the fossil fuel industry continue to pour their resources into expanding oil and natural gas production to maximize profits for their shareholders in the short term, meanwhile using their lobbying power to deny climate change and generally interfere with government efforts to promote development of renewable clean energy sources like solar and wind power.

Moses: But eventually, fossil fuel reserves will run out.

Socrates: Exactly. Talk about a Tragedy of the Commons in the making! And when that happens, who will have emerged as the world leaders in renewable clean energy production? I'm betting on China over the United States.

Moses: It's alarming to think that authoritarian governments may be more successful than democracies at managing their nation's domestic economy. The wealthier a nation becomes, the more it can afford to spend on strengthening its military capabilities. If the tide shifts from liberal democracies being the most powerful nations on earth to illiberal authoritarian nations, it doesn't bode well for human rights and individual freedom.

Socrates: As Vladimir [194] once quipped in the early days of the Soviet Union, "The capitalists will sell us the rope with which we will hang them."

Moses: Wasn't that quote about free market capitalism being supplanted by state communism?

Socrates: Yes. Only nowadays it applies to market capitalism in liberal democracies versus state-managed capitalism in illiberal authoritarian nations. The problem is that multinational corporations controlling the economic policies of the liberal democracies like the US are focused on the bottom line of profitability with respect to the global economy, not domestic priorities relating to the welfare of average citizens.

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[194] **Vladimir Ilyich Lenin** (1870 –1924), Russian revolutionary, politician, and political theorist who served as head of government of Soviet Russia from 1917 to 1922 and of the Soviet Union from 1922 to 1924. Although the quote has been variable attributed to Lenin, Marx or Stalin, the documentation of its origin remains unclear.

Moses: Ah, now I see what you mean. But it's not really a fair comparison to a true liberal democracy. It's a comparison between a corrupt liberal democracy in which multinational corporations, instead of average citizens, set the nation's economic policies, versus state-managed capitalism in which authoritarian leaders set the nation's economic policies.

Socrates: Well-said, Moses.

Moses: Then the question is, how do you uncorrupt those liberal democracies so that average citizens can reset economic policies to create a *win-win* outcome for both wealthy and poor citizens alike?

Socrates: Indeed, that's the key issue - how to prevent wealthy special interest groups from unduly influencing government policies to their own advantage, regardless of negative consequences to average citizens. Not an easy issue to solve.

Moses: How about reforming campaign finance laws, like abolishing SuperPACs and restoring the Fairness Doctrine requiring mass media outlets to give equal time to both sides of an issue? And defeating voter suppression legislation? Do you think that might solve the problem?

Socrates: It would be a good place to start, for sure. After all, the citizens ultimately hold the power of the vote in a democracy. Frankly, though, I'm not sure that it would be enough, given how thoroughly special interest groups have become engrained into liberal democratic governments these days.

Moses: Suppose, though, that you could just wave a magic wand and start afresh, rebuilding an uncorruptible democracy from the bottom up? What would you do to ensure that the voices of all the people prevail?

CHAPTER 22: Egalitocracy

Socrates: What would I do if I could wave a magic wand to create the ideal incorruptible democracy that works for benefit all its citizens? A very interesting question indeed.

Moses: And?

Socrates: You know the old adage, *Those would ignore history are doomed to repeat it*? That's where I would start.

Moses: How, exactly?

Socrates: Here's how I see it. Sacrificing egalitarianism in favor of political alpha hierarchies is what got you into the Devil's Bargain mess that you're in right now, with wealth disparity at a record high and human civilization spiraling towards a global Tragedy of the Commons threatening the entire planet. Perhaps that is telling you something - that egalitarianism was too important a stage in human history to let it become an evolutionary dead end for you.

Moses: But if egalitarianism becomes impractical once the population size exceeds a hundred fifty people, how is that possibly going to help us? Besides, you said that our simple forager ancestors only applied the Golden Rule to members within their own band, not to outsiders. In other words, they were just as tribal and war-like as modern humans today.

Socrates: Just because the simple form of egalitarianism practiced by your ancestors isn't directly adaptable to a complex highly diversified modern society doesn't mean that you can't build upon its virtues. Perhaps you just need to make a few adjustments.

Moses: Like what kind of adjustments?

Socrates: Here's what we know. The Wisdom of Crowds phenomenon depends on individual members of the group knowing each other well enough to judge who is reliable and who is not. However, achieving that level of interpersonal familiarity and trust is only possible in social groups of less than one hundred fifty or so people. More than that, the free-riders, like your special interest groups, become too hard to police, and pure egalitarianism breaks down.

Moses: Indeed, that is our dilemma.

Socrates: So how many voters typically decide the outcome of an election in a modern democracy like the United States?

Moses: Way more than one hundred fifty. Maybe some very small towns elect a mayor or sheriff with less than one hundred fifty voters, but for city, state or national elections, it's usually thousands or millions of voters.

Socrates: And how well does each of those voters know the candidate?

Moses: Not very well. Just what they see on television or read in the news.

Socrates: Enough for the typical voter to judge whether a candidate can be trusted or not?

Moses: I doubt it. Without personal knowledge of the candidate's character, it's hard to know whether or not they have a hidden agenda.

Socrates: What would it take, do you think, to know the candidate well enough to reliably judge his or her intentions?

Moses: I guess they'd have to be one of your one hundred fifty closest acquaintances, like in a typical egalitarian community of simple foragers.

Socrates: Then instead of abandoning egalitarianism, why not make it the fundamental building block of a new political system?

Moses: I don't quite follow you. How can you scale up a system that works only for a maximum of one hundred fifty people to millions or billions of citizens living together in complex highly diversified modern societies like the United States?

Socrates: As a start, how about organizing all adult citizens in the nation into groups of less than one hundred fifty citizens? Call them egalitarian councils – say fifty citizens per council, similar in size to the simple forager bands in which egalitarianism first evolved and thrived. Fifty is small enough for consensus decision-making to be practical and also for each member to get to know everyone else well enough to keep the self-serving free-riders in line.

Moses: Okay, then what?

Socrates: The first order of business is to decide how to select the members of each egalitarian council in a way that takes advantage of the Wisdom of Crowds.

Moses: To meet the *decentralization, diversity, independence,* and *aggregation* criteria, you mean?

Socrates: Exactly.

Moses: Then one thing that I wouldn't do would be to let groups of friends form their own councils.

Socrates: Eminently sensible. Groups of like-minded friends would just amplify their like-minded confirmation biases and promote Groupthink instead of the Wisdom of Crowds.

Moses: How about random selection, then? That way you end up a mixture of men and women, conservatives and liberals, wealthy and poor, highly and less highly educated, from diverse professions, religions and ethnic/racial backgrounds and so forth? That would ensure that each egalitarian council consists of a diverse mix of individuals. And if you selected them from the same general locality, they would share common cultural interests in how their local community should operate.

Socrates: Perfect, you've just taken care of the *diversity* criterion! Congratulations. Only three more criteria remaining. Go on, how would you define ground rules for how each egalitarian council should operate?

Moses: I suppose that the main ground rule would be that all fifty members are encouraged and expected to voice their frank opinions, so that everyone gets a say. Then the members can vote by majority rule to come up with a consensus opinion. That would align with the *decentralization, independence* and *aggregation* criteria.

Socrates: Just like our egalitarian ancestors did. So far, so good.

Moses: Except that all we've really done is to reinvent the wheel. What are we supposed to do next? Assuming that there are about two hundred fifty million US citizens over the age of eighteen, that would come to about five million egalitarian councils in all.

Socrates: Patience, Moses, that was just the first step, creating the fundamental building blocks. Now we that have five million egalitarian councils engineered to meet the criteria for the Wisdom of Crowds individually, our next task is to link them together in a fashion that preserves the same criteria collectively. The five million individual egalitarian councils already embody *diversity*, since they come from all different regions of the nation with different lifestyles and cultural perspectives. But we still have to ensure that the other remaining criteria are preserved.

Moses: How are we supposed to take five million consensus decisions and condense them into a final consensus decision that's democratically fair to everyone?

Socrates: Want a hint?

Moses: Sure.

Socrates: Biology generally prefers bottom-up over top-down solutions – that is, taking a successful strategy at one level and reapplying it to the next level of integration, and the next level after that from the bottom up (Figure 18-1). Similar to a neural network machine deep learning algorithm. The first hidden layer processes information from the bottom input layer, and second hidden layer then processes the outputs from the first hidden layer, and so forth to the final top output layer. Maybe we can apply the same principle here.

Moses: You mean by creating multiple layers of egalitarian councils?

Socrates: Why not? Say that after each primary egalitarian council arrives at its own consensus opinion, they democratically elect one of their members, for a specified term, to represent their consensus opinion to a second layer of egalitarian councils. If each level-2 council also consisted of fifty elected representatives from fifty different primary councils, that comes to 100,000 level-2 councils. Each of the level-2 councils would then evaluate the independent consensus decisions from the fifty primary councils it represents and democratically condense them into its own level-2 consensus opinion. It would satisfy both the *decentralization* and *independence* criteria.

Moses: Then what? You still end up with 100,000 separate level-2 consensus opinions.

Socrates: Yes, but in the process, we aggregated consensus decisions from 5 million independent, diverse and decentralized primary councils into 100,000 level-2 consensus decisions. Then we just repeat the process (Figure 21-1). Each level-2 council elects one of its members, for a limited term, to represent its consensus opinions to a third layer of councils, each containing fifty members.

Moses: I see where you're going. The third layer would consist of 2,000 level-3 councils that would aggregate the consensus opinions from the 100,000 independent, diverse and decentralized level-2 councils into 2,000 separate consensus opinions. Then each level-3 council could then elect one of its members to represent its consensus opinion to a fourth layer of councils, each containing fifty members. They would in turn aggregate the 2,000 consensus opinions into forty consensus decisions, one for each level-4 council!

Socrates: Exactly. One more layer and we're done! The fifth layer would consist of a single level-5 egalitarian council with one elected representative from each of the forty level-4 councils. They would aggregate the consensus opinions from the forty level-4 councils into a final consensus decision. All in all, 250 million decentralized, diverse, independent, individual opinions democratically aggregated, layer by layer, into a single consensus decision, taking advantage of the Wisdom of Crowds at each step along the way!

Moses: Intriguing, I have to admit. How would these egalitarian councils actually work?

Socrates: It would take some trial-and-error, for sure. But say that each adult's civic responsibility was to confer with members of their primary council for one or two hours each day. The goal would be to get to know each other's personalities well enough to encourage a robust and forthright discussion of the pros and cons of various issues, and then arrive at a consensus opinion by majority vote. A democratically elected representative would then take the primary council's consensus opinion to the level-2 council, and so forth through the higher layers.

Moses: What about the representatives who are elected to councils in the higher layers?

Socrates: If the time commitment is one or two hours a day, then it would be workable even for an individual who belonged to all five layers of councils. And the councils in the higher levels wouldn't have to deal with every single issue from five million councils. The primary level-1 councils could focus mostly on local neighborhood issues, the level-2 councils on city-wide issues, the level-3 councils on state-wide issues, the level-4 councils on regional issues, and the level-5 council on national issues. In other words, local issues would be handled locally and only move up to the next layer if their implications had broader impact on whole cities, states, regions or the nation. That would preserve local community autonomy, as long as it abided by broad ethical issues and basic human rights ratified by the highest level councils.

Moses: And what about national issues that affect everyone? Like wealth disparity, universal health care, free higher education, protecting the environment, gun control, abortion or whether taxes should go up or down, and so forth.

Socrates: Broad issues like those would also be passed in both directions, from higher layers down to the primary councils and vice versa. In neural network terms, it would be more similar to a recursive neural network (RNN) incorporating both feedforward and feedback links, rather than a purely feedforward neural network.

Moses: That would certainly be a radical departure from present day representative democracies where voters elect politicians to make the important decisions for them.

Socrates: Exactly, that's the whole idea. The decisions affecting each citizen's life would be directly made by 5,102,041 decentralized, diverse and independent egalitarian councils, each consisting of no more than fifty people who know each other well enough to establish a high level of trust between them. That feature will make it much more difficult for special interest groups and wealthy individuals to influence political decisions!

Moses: I like it! A multi-level version of egalitarianism designed to govern a nation democratically from bottom up.

Socrates: And designed to optimize the Wisdom of Crowds and minimize the corrupting influence free-riders and special interest groups, so that the true will of the people prevails!

Moses: We should give it a new name. Since it's basically a fusion of egalitarianism with democracy, how about egalitocracy?

Socrates: Why not? Egalitocracy it is!

Moses: Do you really think it's practical, though? I can see egalitarian councils making wise, fair decisions when they are advised by experts who all agree on the best solution to a problem. But what about issues that are so complex that even the experts don't agree on the best solution? Like economic policies, for example. Conservative economists firmly believe that cutting taxes and reducing government spending is the key to maximizing prosperity, whereas the liberal economists advocate the opposite. How are average citizens in an egalitarian council, who are not professionally-trained economists, supposed to know which set of experts to trust?

Socrates: Ironically, that's exactly the situation in which the Wisdom of Crowds works best, when there is diversity of opinion and even the experts don't agree. Jonathan [195] has put it this way:

> "Rather, what I'm saying is that we must be wary of any individual's ability to reason. We should see each individual as being limited, like a neuron. A neuron is really good at one thing: summing up the stimulation coming into its dendrites to "decide" whether to fire a pulse along its axon. A neuron by itself isn't very smart. But if you put neurons together in the right way you get a brain; you get an emergent system that is much smarter and more flexible than a single neuron. In the same way, each individual reasoner is really good at one thing: finding evidence to support the position he or she already holds, usually for intuitive reasons. We should not expect individuals to produce good, open-minded, truth-seeking reasoning, particularly when self-interest or reputational concerns are in play. But if you put individuals together in the right way, such that some individuals can use their reasoning powers to disconfirm the claims of others, and all individuals feel some common bond or shared fate that allows them to interact civilly, you can create a group that ends up producing good reasoning as an emergent property of the social system. This is why it's so important to have intellectual and ideological diversity within any group or institution whose goal is to find truth (such as an intelligence agency or a community of scientists) or to produce good public policy (such as a legislature or advisory board)."

Moses: Even so, that's only plausible if members in each egalitarian council are well-informed enough to assess meaningfully what different experts think about a given issue. How are average citizens with no background in esoteric subjects like economic theory supposed to do that?

Socrates: The same way politicians do today – by having professionals with appropriate expertise act as their staffs. The staffs would summarize the pros and cons of an issue from the expert's viewpoints, written in non-technical language that citizens from different backgrounds can all comprehend. Just like the propositions on many state and local ballots today.

Moses: And you think that these egalitarian councils could handle big national issues, like wealth disparity, universal health care, free higher education, protecting the environment, gun control, abortion or whether taxes should go up or down?

Socrates: Why not? Would you rather leave those decisions up to traditional politicians whom the average citizen can't know well enough to trust and may be beholden to special interest groups? I say let average citizens debate the pros and cons directly among their group of fifty individuals, each of whom they know well enough to assess their character, personality traits, intelligence, common sense, etc., and then come to their own consensus.

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[195] **Jonathan Haidt.** *The Righteous Mind: Why Good People Are Divided by Politics and Religion*. Knopf Doubleday Publishing Group, 2012. p. 105-106 in Kindle Edition.

Moses: Give me an example, then. Say that you wanted to tackle the growing wealth and income disparity. How would an egalitocracy go about it?

Socrates: If it were up to me, I'd hold a national referendum among the five million primary egalitarian councils to decide on the fairest way to distribute wealth and income. Start simply, like: *Currently, three people control as much wealth as the poorest half of the US population. The top half owns 98% of the wealth and receives 80% of the income. Which of the following options do you support?* 1) *No change in the present situation;* 2) *Sharing everything equally, like our egalitarian ancestors did;* 3) *Something in between.* What do you think the average US citizen would choose?

Moses: The third option.

Socrates: Okay. Now we discuss the reasons. Say it's your turn to speak to the fellow members of your egalitarian council. How do you feel about three people controlling as much wealth as half of the US population, and why?

Moses: It just seems unfair. To me, every citizen ultimately owes more to society than society owes to them. No matter how talented, visionary and hard-working a person may be, society provided the resources to raise and educate them, as well as everything else required for them to become successful. Without society, they couldn't even have learned to speak or write, much less acquired the skills to build a business and accumulate their fortune. If other citizens are barely scraping by just to survive, why should they be allowed to accumulate unlimited wealth that's more than they could possibly spend in several lifetimes?

Socrates: Very reasonable. And what about the other extreme, with everyone sharing everything equally. How do you feel about that?

Moses: Also unfair. Unlike our egalitarian ancestors in which everyone did pretty much the same thing, modern society is highly differentiated, and some people make more important contributions than others. They should be rewarded for their talent, ingenuity, dedication and drive. Besides, if everything was shared equally, there would be no incentive to do anything beyond the bare minimum. Without the incentive to work, the economy would disintegrate.

Socrates: Very reasonable arguments as well.

Moses: Thank you. But how does that help us?

Socrates: It helps a lot, since you've boiled the income/wealth disparity issue down into its Yin and Yang essence - two competing but complementary opposites: social justice versus individual incentive. Now you just have to figure out how to balance them. Go ahead, give it a shot. Say that it's your turn to speak again. What do you think is fair regarding social justice?

Moses: I'd say that ideally, every citizen should be guaranteed the basic necessities of life – food, shelter, education and healthcare. That way, each citizen can realize their full potential and contribute to society to the best of their abilities. And the nation benefits by developing the talent pool of its citizens as fully as possible.

Socrates: Do you think that as the wealthiest nation on earth, the United States has the resources to provide the basic necessities of life to every citizen?

Moses: Of course. But we're hardly leading the way. Other developed nations are much further along than we are. Many advanced social democracies already provide universal free health care and universal free higher education. And some are even beginning to experiment with a universal basic income [196]. Of course, citizens of those nations pay much higher taxes, which is the reason why the United States hasn't followed suit.

Socrates: On the other hand, if both universal health care and higher education were guaranteed, you'd be halfway there, right? Then all you need is a universal basic income sufficient to cover adequate food and shelter.

Moses: True, but who's going to pay for it? Not only that, if the basic necessities of life are provided free to each citizen, then what's the incentive to work? It's a set up for a vicious cycle – if you don't have enough workers to maintain a productive economy, you won't be able to provide the basic necessities to everyone for free, and then the whole system falls apart!

Socrates: Fair enough. If I may ask, what about you? Would you still work if society provided you with all of the basic necessities for free?

Moses: Me? Of course I would. To me, it's personally fulfilling to know that I'm contributing to the society's welfare in a meaningful way.

Socrates: So even if you had no financial need to work, you would keep working anyway?

Moses: What else would I do – go surfing everyday? I'd get bored, even with a talking sea lion to keep me company. No offense.

Socrates: No offense taken. But don't you think that, by and large, other citizens would feel the same way?

Moses: Maybe if they like their jobs. But a lot of jobs necessary for society to function are pretty boring. It seems like a risky gamble to provide everyone with the basic necessities of life and then hope that enough people still want to work so that the economy can function.

Socrates: There's an easy way to get around that.

Moses: How?

Socrates: By phasing in the universal basic income gradually.

Moses: What do you mean?

[196] **Nathan Heller**. Take the Money and Run. *The New Yorker*, July 9, 2018. p. 66.

Socrates: Say that the United States was like other advanced social democracies and already provided universal health care and higher education for free. Citizens would still need an income-generating job to afford food and shelter, right?

Moses: Sure.

Socrates: Then if you start with a universal basic income at a low amount that's not quite enough to fully cover the cost of food and shelter, citizens would still need to earn additional income to make ends meet.

Moses: Okay.

Socrates: Then gradually increase the universal basic income to see how many people decide to give up their jobs.

Moses: You won't get very far if most people decide to give up their jobs in favor of a life of leisure once the basic necessities are covered.

Socrates: Fine. Then just lower the universal basic income back to the original level so that people still have to work to survive. But my guess is that a lot of people will desire more out of life than just scraping by on the basic necessities. They will still want to work to earn extra income to afford a higher-than-average standard of living.

Moses: I guess it depends on how high you raise the universal basic income. As it goes up, more and more people will be satisfied and drop out of the workforce.

Socrates: Exactly - that's the beauty of it.

Moses: What do you mean?

Socrates: It's how you regulate the size of the workforce to fill the supply of jobs. When the demand for income-earning jobs matches the supply, that's the sweet spot for the universal basic income level to be set so that the economy continues to flourish.

Moses: In other words, a regulated market approach that matches the supply of jobs to the demand for jobs, by adjusting the level of the universal basic income. Very clever - Adam would be proud of you!

Socrates: More importantly, it also solves another modern problem that's looming before you.

Moses: What's that?

Socrates: Right now prosperous developed countries like yours have a deficiency of good middle class jobs. That's a major reason why the poorer half of US citizens are seeing a decrease in their real income (Figure 19-2). Due to the combination of economic globalization and automation, those good middle class jobs have moved overseas where labor is cheaper, or are being performed by machines instead of human beings. And guess what?

Moses: What?

Socrates: It's just the start. So far, it's mostly been dumb machines replacing repetitive jobs. But now you're entering the age of smart machines outfitted with AI. That means that more and more white collar jobs are going to be replaced as well. Some technology experts have estimated that more than 30% of today's jobs will be eliminated in the next decade [197].

Moses: I don't know - that fear has been circulating since the dawn of the Industrial Revolution. Whenever technological advances have eliminated jobs in the past, new jobs have always sprung up to replace them. Like farmers transitioning to factory workers after agriculture was mechanized, or factory workers transitioning to service industries when manufacturing was automated. Do you really think it will be any different with smart machines?

Socrates: The technology experts argue that this time is different. In the past, machines could only replace human muscle power. Now they are replacing human brain power as well. In the future, it's not clear whether the average worker's skill set will surpass what a smart machine equipped with AI can do more efficiently and cheaply.

Moses: Humans will still need to design the smart machines.

Socrates: True, at least for the time being. But not everyone is suited to become a scientist or engineer capable of designing smart machines. So if society requires every able-bodied citizen to have a wage-earning job or some other form of income in order to afford the basic necessities of life for themselves and their families, what's going to happen when there aren't enough decent jobs to go around?

Moses: I see what you mean. If that happens, the current system will become untenable. Unless society changes to ensure every citizen is guaranteed the basic necessities of life, whether they have an income-earning job or not, it's a disaster in the making.

Socrates: Or a blessing in disguise, if you handle it right.

Moses: What do you mean?

Socrates: Think about it - society will have advanced to the stage where a substantial portion of the population are free to pursue their creative interests and enjoy life to the fullest, instead of having to slave away at some dreary job just to survive! That should be a cause for celebration, not despair - a utopia for human creativity could be at your doorstep, if you handle it right!

Moses: But exactly how is society supposed to pay for it?

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[197] McKinsey Global Institute Report *Jobs Lost, Jobs Gained: Workforce Transitions in a Time of Automation*. December 2017.
https://www.mckinsey.com/~/media/mckinsey/industries/public%20and%20social%20sector/our%20insights/what%twentiethe%20future%20of%20work%20will%20mean%20for%20jobs%20skills%20and%20wages/mgi%20jobs%20lost-jobs%20gained_report_december%202017.pdf

Socrates: By shifting the emphasis away from Greed is Good and back towards the Golden Rule.

Moses: You mean taking from the wealthy and giving to the poor through higher taxes and such?

Socrates: A brilliant suggestion!

Moses: That's what I was afraid of.

Socrates: What do you expect, nothing is free! And those who are fortunate should feel good when they give to those who are less fortunate – isn't that what parents teach their children – that virtue is its own reward? It's the central tenet of the Golden Rule.

Moses: Except that raising taxes is very unpopular. The economists will argue that higher taxes slow growth, because businesses have less to profit to invest and individuals have less to spend to fuel the economy. And to the taxpayer, higher taxes mean less income to spend today with some vague promise that sometime in the future it will be repaid in the form of government-sponsored benefits. And who trusts a bureaucratic government agency that's not subject to market competition to spend tax revenues wisely? A bird in hand is better than two in the bush, as they say.

Socrates: All valid concerns, especially now, with wealthy special interest groups manipulating the economic policies of democratic governments to their advantage, rather than to the advantage of all citizens.

Moses: Then how do you get the government to become part of the solution, instead of part of the problem?

Socrates: That's why we invented egalitocracy, remember?

Moses: Sure, but the problem is that we're still a long way from it.

Socrates: Even so, we can dream, can't we? For the sake of argument, let's imagine we are already there, and have a government that serves all of the people, instead of just the wealthy and powerful. The challenge facing our egalitarian councils is to restructure taxation to generate enough revenue for universal health care, higher education, and a universal basic income for each citizen. The obvious candidates for taxes are income, wealth, and/or inheritance. But they have to be balanced in a way that fulfills the social justice requirements without destroying individual incentive central to economic productivity. Where do you want to start?

Moses: I have no idea.

Socrates: Come on, use your imagination. I'm sure we can come up with some general guidelines.

Moses: Like what?

Socrates: Let me ask you a question. Do you think that I am 250,000 times more valuable than the average sea lion?

Moses: What does that have to do with taxes?

Socrates: Just bear with me. Do you think that I am 250,000 times more valuable than the average sea lion?

Moses: You're a pretty special sea lion, I have to admit.

Socrates: But if I never existed, would sea lion life go on as usual?

Moses: I suppose so.

Socrates: Exactly. Life would go on. By the same reasoning, your three wealthiest US citizens are each worth in the vicinity of $100 billion apiece, compared to the average citizen whose net worth is around $400,000 [198]. Are those three individuals really 250,000 times more valuable than your average US citizen? Or, in terms of annual income, are they really 220,000 times more valuable than your average US citizen earning around $50,000 a year [199]?

Moses: When you put it that way, it does seem a bit extreme. It's not like the industries that they built wouldn't exist if they had never been born. Some other talented entrepreneur would just have taken their place.

Socrates: Exactly. It's like saying that where it not for Albert Einstein, modern physics would not exist. It might have taken another decade or two, but eventually some other talented physicist would have come upon the same ideas. Do you really think that you'd still driving horse and carriages were it not for Henry Ford, or that personal computers wouldn't have transformed modern society if Bill Gates or Steve Jobs had never been born?

Moses: I suppose that if it weren't for society's investment in raising and educating them, none of those titans of the business world would even be able to speak intelligibly, much less create a successful business or industry.

Socrates: Very true. No matter how you look at it, their debt to society is ultimately much greater than society's debt to them. I'm not saying that they don't deserve to be rewarded for their creativity and hard work, but by a factor of 250,000? Really? That seems a bit excessive to me.

Moses: What do you think would be fair?

Socrates: A perfect question to pose to the five million egalitarian councils, don't you think?

Moses: I'm sure there'd be a wide range of opinions.

Socrates: If you were to make a rough guess, though, what do you think would be fair?

Moses: I don't know – maybe somewhere between a hundred and a thousand.

Socrates: Fair enough, let's take two hundred as a guess.

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[198] See https://en.wikipedia.org/wiki/List_of_countries_by_wealth_per_adult. The median and mean income per adult in the US were $65,904 and $432,365 in 2019.
[199] See https://www.thebalance.com/what-is-average-income-in-usa-family-household-history-3306189.

Moses: Okay, then what?

Socrates: Then we add an eleventh commandment to the ten handed down to your namesake: *We hold this truth to be self-evident, that in weighing the balance between a person's individual achievements and contributions to society on the one side, and their ultimate debt to society on the other side, no person shall be entitled to receive an annual income more than two hundred times that of the average citizen.*

Moses: So that's our general guideline?

Socrates: It can be whatever the egalitarian councils decide. But if we use two hundred, it would translate to a maximum allowable annual income of $10 million a year if the average income per capita is $50,000 a year, near what it is today in the United States. Still enough for a pretty luxurious life style.

Moses: In other words, a graduated income tax that progressively increases to 100% for everything over $10 million. That sounds pretty draconian actually.

Socrates: Does it? US citizens have put up with bigger tax hikes in the past. Take 1944-45, for instance, when the maximum income tax bracket was raised to 94% for income exceeding $200,000, equivalent to $2.85 million in today's dollars. That tax bill increased the percentage of the US citizens paying income taxes from 7% to 64%.[200] Now that was a big leap!

Moses: Even so, that was during World War II when raising taxes was a patriotic duty needed to bring the war to a close. It would be a much harder to gain public support for an income tax hike like that now.

Socrates: It's really not as bad as you think it is. Let me illustrate. Right now the top half of the US population receives 80% of the income, and the bottom half receives 20%, i.e. a 4:1 ratio (Figure 19-2). With a mean annual income per capita today of nearly $50,000, a 4:1 ratio translates to the top half earning an average of $80,000 per year, and the bottom half earning an average of $20,000 per year. To provide a universal basic income of $10,000 per year to every citizen, then, would require redistributing $10,000 from the top half to the bottom half. That means raising the average income of the bottom half from $20,000 to $30,000, and decreasing the average income of the top half from $80,000 to $70,000. It's only an additional 12.5% income tax on the top half! In other words, except for the 16,000 or so Americans who currently earn more than $10 million a year [201], the top income tax bracket would increase from 35% to 40%. That's considerably lower than the 70% top income tax bracket prior to the 1980s.

Moses: And what about those 16,000 Americans whose annual income is more than $10 million?

Socrates: They are out of luck.

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[200] See https://teachinghistory.org/history-content/ask-a-historian/24489.
[201] See https://www.fool.com/investing/2019/01/09/who-would-pay-a-70-tax-rate-on-income-over-10-mill.aspx.

Moses: So let me get this straight. Take some entrepreneur who starts a business like Microsoft or Amazon that becomes worth billions. What happens to them?

Socrates: They would manage the business and its assets, but they could only draw a maximum of $10 million a year as personal income. Of course, the business would still have to pay corporate taxes on its earnings.

Moses: So the entrepreneur wouldn't really own their business in the conventional sense, where they could do whatever they like. They'd be more like the stewards of the business for the benefit of society, with anything over $10 million a year remaining as assets of the business.

Socrates: Exactly. And those assets over $10 million would be re-invested to develop the business further and promote economic growth in the process!

Moses: So the business owner couldn't buy a $50 million yacht for their personal use, for example?

Socrates: Only if they saved $5 million a year from their annual salary for ten years. Why, are you feeling sorry for them?

Moses: Not really. They should still be able to live a pretty luxurious life style on $10 million a year. And I suppose you could reward them in some other way, to publicly acknowledge their contributions to their nation's welfare.

Socrates: Sure, why not? How about life-time membership in an exclusive club for the titans of industry and other masters of the economic universe who are successful enough to achieve the maximum annual income level.

Moses: We could call it the Golden Rule Club! A status symbol, like belonging to the Forbes 400 list today!

Socrates: But instead of reflecting their personal wealth, it will acknowledge the wealth that they've contributed to the welfare of society through their business accomplishments. Since they're a competitive lot by nature, they can compete to see who ranks numero uno as the greatest benefactor to their nation and to the world, just like they compete in philanthropy today.

Moses: And what about their families? Could children continue to manage the family business after their parents die?

Socrates: If it was a privately-owned business, I don't see why not. Family businesses could remain family-run by the children, assuming they wanted to. But they couldn't take more than $10 million a year in personal salary.

Moses: And if it was publicly-owned?

Socrates: Then the shareholders would decide on the new management.

Moses: What if the surviving family members wanted to sell the business instead?

Socrates: It all depends on what your five million egalitarian councils decide to do about inheritance.

Moses: What do you mean?

Socrates: Remember Ivan the average investor who invested his inherited $100,000 in the stock market and then just sat back to watch his wealth grow at the return on investment rate r of 9.8% annually? Is it really fair that he ended up so much wealthier than Eddie the average entrepreneur, who worked his butt off to build his own business, but whose wealth grew at the economic growth rate g of 2.5%?

Moses: Ah yes, the $r > g$ problem.

Socrates: That's what the egalitarian councils will have to wrestle with - how to manage the $r > g$ problem so that income and wealth disparity don't get out of hand like they have today. If children are allowed to inherit their parent's wealth, then rich kids like Ivan will continue to have a big advantage. The wealthiest ones could just put their inheritance into an investment firm and sit back to collect up to $10 million a year for the rest of their lives.

Moses: I see what you mean. Then we'd be back to the investors having a major advantage over entrepreneurs and workers. If it were up to you, what would you do?

Socrates: Personally, I think abolishing inheritance altogether is the fairest option. That would ensure an even playing field for each new generation, and at the same time provide a strong incentive for each individual, including the rich kids, to develop the skills to be successful on their own terms if they want to earn more than the universal basic income.

Moses: I don't know how most parents would feel about that. A major reason that parents work hard is to give their children a better life.

Socrates: If the parents are wealthy, then while they are alive, they can pamper their children to their hearts' content. They can send them to the best schools, expose them to culture and travel, and enrich their lives however they think best to prepare them to achieve their full potential as adults.

Moses: I still think wealthy parents would be very upset at the prospect of their children having to face a sudden major decline in their standard of living if they were orphaned.

Socrates: Perhaps. But remember, those children wouldn't starve – they'd still be guaranteed all of the basic necessities of life needed to become successful like every other citizen. Besides, realistically speaking, most children are already well into adulthood, often their fifties or sixties, by the time that their parents pass away. By that age, shouldn't they have developed their own successful careers, especially given the advantages that their wealthy parents were able to give them when they were young?

Moses: That's a good point. And if the next generation knew that they couldn't depend on inherited money, it would certainly motivate them to become economically self-reliant on their own. Maybe that aspect would appeal to conservatives, since they are always stressing the importance of individual initiative and personal responsibility.

Socrates: Hard to imagine conservatives ever voting to abolish inheritance! But making the playing field even should certainly appeal to liberals. With universal health care, education and a universal basic income, all children would have access to the essential tools to become successful later in life, regardless of the income status of their parents. Even those who are unfortunate enough to lose their parents at a young age will be well provided for. That should reassure all parents, rich or poor.

Moses: Seems like a *win-win* for everyone. The nation would be developing its human capital optimally. Children from wealthy families would be incentivized to develop successful careers on their own since they couldn't rely on a large inheritance. Children from poor families would be guaranteed the basic necessities of life including access to a good education to help them realize their full potential. Equal opportunity for all children to become successful adults!

Socrates: And there's another advantage to abolishing inheritance.

Moses: What's that?

Socrates: Currently, private wealth in the United States is estimated to be around $100 trillion. With about 0.85% of the US population dying each year [202], that means that around $850 billion would end up in the government's hands if inheritance were abolished. That's a pretty big windfall compared to the current situation in which the government collects only about $64 billion a year in federal estate taxes.

Moses: A great way to jump start the universal basic income program!

Socrates: Good thought, Moses, but that money will be needed for something else. We haven't discussed how to pay for universal health care and higher education yet.

Moses: That's true. Health care is a huge expense, especially in United States. Would $850 billion be enough to cover it, do you think?

Socrates: Not the way that the US health care system currently operates. Last year, the United States spent $3.65 trillion on health care, 17.9% of its GDP, of which $1.1 trillion came from the federal government [203]. That's $11,000 per person, over twice what other advanced social democracies with government-run single payer health care systems spend per person. And despite the lavish cost, overall health care quality in the United States currently ranks at #35 in the world, between Costa Rico and Slovenia [204], well below those of most developed nations with government-funded single payer health care systems.

Moses: That's pretty pathetic.

Socrates: A prime example where private sector has failed abysmally. They've had over fifty years to solve the problem in the United States, but have yet to develop a cost-

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[202] See https://www.cdc.gov/nchs/fastats/deaths.htm#:
[203] See https://www.taxpolicycenter.org/briefing-book/how-much-does-federal-government-spend-health-care AND http://fortune.com/2019/02/21/us-health-care-costs-2/
[204] See https://www.who.int/healthinfo/paper30.pdf

effective health care system that comes even close to what government-funded single payer health care systems have achieved in so many other developed nations.

Moses: That's because it's been such a cash cow for special interest groups like private health insurance and big pharma, whose lobbies continue to subvert all legislative attempts to make the necessary reforms to the private health care system or transition to a single payer government-run system, like extending Medicare to all citizens. That $11,000 per person cost of health care is more than the universal basic income of $10,000 that we were talking about! Where's that supposed to come from? Even if you add all of the $850 billion from inheritance to the $1.1 trillion that the government already spends on health care, you're at $1.95 trillion, nowhere near the $3.65 trillion that the US spends on health care now.

Socrates: True, but here's how I figure it. If the US were to adopt a single payer government-funded system like other developed countries, they should be able to reduce health care costs by about half, to $1.825 trillion a year. Then $1.95 trillion would be enough to cover it, with about $125 billion left over.

Moses: I see. But even if that worked out, though, we haven't talked yet about the cost of providing higher education for free. How much is that likely to cost?

Socrates: That's much cheaper, actually. According to one recent estimate [205], it would take around $125 billion a year, both to forgive current student debt and make higher education free in public universities.

Moses: Wow! Then it might just work out. Although it's a moot point until some nation actually decides to give egalitocracy a try. Pretty unlikely that's going to happen any time soon.

Socrates: But not impossible. Remember that in a legitimate democracy, people do have the power to change what they don't like! All they have to do is vote.

Moses: True, but it seems like a lot to ask, to vote to transform the very foundations of the current system to a completely new form of democracy.

Socrates: That's probably what your primate ancestors said to each other when they were still locked into alpha hierarchies and just beginning to substitute gossip for grooming – I'm sure that none of them ever imagined that a phase transition to egalitarianism was about to change their lives. Then along came the Egalitarian Transition, and poof! - alpha hierarchies became passé and egalitarianism ruled the day. Of course, I'm not claiming that it happened overnight. It must have taken many generations for egalitarian bands to finally displace all of the alpha hierarchies. But if humans truly desire a government *"of the people, by the people and for the people"*, as Abe so eloquently put it [206], clearly something has to change.

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[205] See https://www.cnbc.com/2019/04/23/elizabeth-warren-proposes-free-college-and-eliminating-student-debt.html

[206] **Abraham Lincoln** (1809-1865), 16th president of the United States from 1861-1865 during the American Civil War.

CHAPTER 23: Possible Worlds 1

Moses: Do you really think that the same sort of thing could happen today, a phase transition to egalitocracy, like a modern version of the Egalitarian Transition?

Socrates: Who knows? It seems to me, however, that a lot of the elements are already brewing.

Moses: Like what?

Socrates: Competing yet complementary opposites striving to evolve a stable new balance.

Moses: I should have guessed - the Yin and Yang Axiom again. How does it apply here?

Socrates: Pretty similar to what happened during the Egalitarian Transition, just on a more integrated scale.

Moses: How do you mean?

Socrates: Before the Egalitarian Transition, your ancestors were typical primates, beating up on each other to compete for the alpha position in their hierarchical community. Then you evolved the capacity for complex language, conferring the gift of gossip and the ability to transmit third-party information. Gossip allowed you to form large coalitions that could dominate any would-be alpha, which triggered the Egalitarian Transition and rapidly transformed you into the animal kingdom's top predator. Voilà, complementary opposites interacting with each other to achieve a new balance – the natural tendency of your Might Makes Right biological genes promoting selfish alpha behavior brought under control by gossip-driven cultural memes promoting the Golden Rule. It turned you into highly cooperative egalitarian bands whose members were able to dedicate their collective intelligence to the common good of the community. That's what allowed them to convert tools into weapons for hunting, warfare and defense against intruders, including other egalitarian bands competing for the same resources.

Moses: So instead of individuals beating up on other individuals within the same community, like other primates, we became egalitarian communities beating up on other egalitarian communities.

Socrates: Exactly. And it worked. Your egalitarian days were a very successful phase of your history for hundreds of thousands of years. In fact, so successful that, ultimately, egalitarianism planted the seeds of its own destruction, by refining your cognitive Wisdom of Crowds collective reasoning skills to the point that ten thousand years ago, you were able to invent agriculture. That's when the Devil's Bargain precipitated another phase transition that transformed you into the full-fledged eusocial superorganisms that you are today. But it came at the cost of upsetting the delicate balance between your biological Might Makes Right genes and the cultural Golden Rule memes that had made egalitarianism possible. As egalitarian simple forager bands coalesced into tribes and then nation-states, communities became too large and specialized for those Golden Rule memes to maintain egalitarian harmony, and the resurgence of your biological Might Makes Right genes in the form of Greed is Good memes overpowered the Golden Rule ethos. And so the balance shifted back to alpha hierarchies led by big men, chiefs, kings, dictators, politicians and so forth.

Moses: In other words, we regressed, back to individuals competing against individuals to be alphas within nation-states, and nation-states competing against nation-states to be alphas among nation-states.

Socrates: Precisely. The result ever since has been political and economic competition on progressively larger scales, spiked with greed, treachery, warfare, enslavement, genocide, racism, colonialism and imperialism. And now that the Industrial Revolution and global capitalism have made you flush with unprecedented economic prosperity, you continue along the same selfish lines, with tribalism and xenophobia fueling increasing wealth disparity, climate change, and environmental destruction. The consequences have been disastrous, with massive extinction throughout the Biosphere, and the real possibility of an irreversible global Tragedy of the Commons. All because you've allowed those Might Makes Right selfish genes hard-wired into your DNA to come roaring back!

Moses: I get what you are saying, but how can you expect otherwise? Modern human societies whose economies are based on capitalism can't be guided solely by a Golden Rule that advocates sharing everything equally. The market's functioning depends fundamentally on self-interest and competition to spur innovation, drive down costs and benefit consumers.

Socrates: And yet the Golden Rule can't be completely jettisoned either, because modern societies still require large scale flexible cooperation between the different segments of the population.

Moses: I suppose that's why we have justice systems, to work out the appropriate balance, with laws that define the upper limit of Might Makes Right/Greed is Good behaviors that a society is willing tolerate. Not to mention laws that define the lower limit of Golden Rule behavior expected of every citizen. Otherwise, human society would degenerate into lawless anarchy.

Socrates: Exactly. That's what James really meant when he said "If men were angels, no Government would necessary." The tricky part is to get the balance right. In capitalist economies, the Greed is Good memes provide the incentive for individual accomplishment, but have to be balanced by the Golden Rule memes to ensure that people treat each other fairly and avoid precipitating a Tragedy of the Commons.

Moses: Then how do you bring them into a proper balance, one that creates a *win-win* for everyone?

Socrates: That's where your next phase transition comes into the picture.

Moses: Triggered by what exactly?

Socrates: It's already been triggered. You're in the midst of it.

Moses: What are you talking about?

Socrates: Sometimes, things have to get worse before they can get better.

Moses: I repeat, what are you talking about?

Socrates: Economic globalization. You are at the crossroads as we speak. On the positive side, globalization has led to unprecedented gains in productivity. The gross world product (GWP) has increased thirteen-fold over the past sixty years, and nearly a hundred-fold since 1900 [207]. Per capita, that's a nearly a five-fold increase just since 1960, and a whopping twenty-fold increase since 1900. Think about it, twenty times more wealth production per person on the planet. Eliminating extreme poverty worldwide by 2030 is now a realistic goal! In the past, humans were always competing over limited resources – there wasn't enough to go around, so you had to fight over the scraps to avoid starving. As late as the 1990s, more than half of the world's population still lived in extreme poverty, trying to make ends meets on less than $1.25 a day. Now, for the first time in human history, there's finally enough to provide everyone with the basic necessities of life.

Moses: Maybe in principle. But that's not what's happening. Extreme poverty may be down, but wealth disparity is worse than ever. People may not be literally starving in developed nations like the United States, but average citizens are struggling nevertheless. Relative poverty is up, even if extreme poverty is down.

Socrates: That's what I meant by things getting worse before they get better. CEOs of multinational corporations and other special interest groups in developed nations like the United States have levied a big penalty on the average citizens of their own countries by using their political influence to align domestic economic policies to serve the global economy. Good domestic blue collar jobs that average citizens previously counted on have been shipped overseas or lost to automation. Tax cuts to the wealthy in the name of stimulating domestic economic growth have depleted vital tax revenues needed to fund federal programs to compensate and retrain displaced domestic workers, or otherwise guarantee them the resources needed to maintain their standard of living. The result is that wealth and income disparity in developed nations has dramatically worsened. In short, thanks to globalization, the trickle down promised to average citizens in developed nations like the United States has evaporated. Of course, redistributing wealth and income from *relatively poor* citizens in developed nations to *extremely poor* citizens in developing nations is not, in itself, a bad thing. But it's pretty galling when the already very wealthy are getting even wealthier in the process and not contributing their fair share.

Moses: Then what's going to turn it around and make it a *win-win* for everyone?

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[207] See https://en.wikipedia.org/wiki/Gross_world_product#Historical_and_prehistorical_estimates AND http://statisticstimes.com/economy/gross-world-product.php

Socrates: The challenge that you face today is distribute your global economic largesse more fairly, in a way that balances prosperity with social justice for all human beings. Now that economic globalization has let the cat out of the bag, it's hard to imagine giving it all up and reverting to the old days of isolationism, protectionism and widespread extreme poverty.

Moses: But how do you fix it when you have nations with fundamentally different political and cultural backgrounds all competing to dominate each other?

Socrates: Like I said, that's where the new phase transition comes in.

Moses: A phase transition to what?

Socrates: Remember how we drew the analogy between the Egalitarian Transition and an ice cube melting? The aggressiveness "will-to-dominate" factor was like the glue holding the alpha hierarchy together, just like the hydrogen bonds that hold the frozen water molecules in place in ice. The bitterness "resentment-against-being-dominated" factor was trying to destabilize the alpha hierarchy, just like the kinetic energy causes the water molecules in ice to vibrate, destabilizing the hydrogen bonds holding them together. And gossip was the interaction factor that allows lower-ranking resentful primates to form coalitions to overpower the alpha, just like heat amplifies the vibrations of water molecules beyond the ability of the hydrogen bonds to keep them rigidly in place.

Moses: Sure, I remember.

Socrates: It's the same principle nowadays, just at a more integrated level – between nations, rather than between individuals.

Moses: Then what's the equivalent of the aggressiveness factor?

Socrates: The desire of a nation to dominate other nations.

Moses: And the equivalent of the bitterness factor?

Socrates: Resentment of a nation against being dominated by other nations.

Moses: Sounds the same as the Egalitarian Transition so far. Is gossip the interaction factor?

Socrates: Not quite. Gossip will a key role shaping the ultimate outcome, but it's not the root cause.

Moses: What is?

Socrates: Economic globalization – the free flow of capital, financing and labor across international borders. That's what's destabilizing the current power hierarchy of nations, especially liberal social democracies.

Moses: How?

Socrates: Here's the issue. To reap the full benefits of global trade, nations have to minimize trade barriers, so that capital, financing and labor can flow freely across national borders to where it can be most efficiently utilized to maximize productivity. Agreed?

Moses: Like you said, that's why the GWP has skyrocketed over the past century.

Socrates: On the other hand, a nation's rank in the world's power hierarchy generally follows its economic status, since wealth buys military strength and geopolitical influence, right?

Moses: Sure.

Socrates: So what's the time-honored way that powerful nations protect their economic well-being?

Moses: Protectionist trade barriers that favor their own domestic industries?

Socrates: Exactly - tariffs, restrictions on the flow of capital and financing and so forth. It's the playbook strategy that has allowed powerful nations to exploit weaker nations throughout modern history. A powerful industrially-developed nation provides the capital to extract a weak agrarian developing nation's natural resources under terms that economically favor the powerful nation. It's trickle down, but between nations instead of individuals. Technically, it's a *win-win* for both. However, since most of the benefit goes to the powerful nation, it strengthens the existing hierarchy. The strong manipulating the weak to cement the pecking order in place.

Moses: So you're saying that when those trade barriers are removed as a result of economic globalization, the cement holding the alpha hierarchy together weakens?

Socrates: Exactly. Just like heat in an ice cube causes the water molecules to vibrate beyond the ability of the hydrogen bonds to hold them in place. China is now the world's second largest economy precisely because the forces of economic globalization made international capital flow, financing and access to cheap labor in China possible. It's the same playbook by which other Asian nations like Japan, Taiwan and South Korea succeeded in the past. But unlike those liberal democracies, China has now demonstrated that an illiberal authoritarian state can compete very effectively in the global capital market. In other words, liberal democracies are not necessary for market capitalism to flourish.

Moses: And as you pointed out before, authoritarian states may actually have an advantage in the global economy.

Socrates: Exactly. When the economic policies of liberal democracies fall under the sway of powerful multi-national corporations, the primary mission of those multinational corporations is to maximize their global profits, not to preserve the domestic well-being of their own nation and its citizens. That's why wealth disparity in the United States has skyrocketed and is causing such intense social unrest, especially among the youth whose prospects for achieving the same standard of living as their parents are steadily diminishing. Of course, leaders of authoritarian nations can behave the same way, and manipulate their economy to enrich themselves and their cronies at the expense of average citizens, like Vladimir [208] has in Russia. But if the authoritarian leaders are crafty and adopt a more far-sighted strategy, like Xi has in China, they can manipulate the global economy to strengthen their domestic economy and advance their national interests, instead of the other way around. That's exactly how China has risen so rapidly to become the second largest economy in the world.

Moses: Is that the phase transition you're talking about - that illiberal authoritarian states are going to win the day over liberal democracies to dominate the global economy and the world power hierarchy?

Socrates: Not exactly. Remember, to qualify as a phase transition, the change has to be qualitative, not just quantitative. A shift in the world power hierarchy away from liberal democracies towards illiberal authoritaritarian states would be a quantitative change in the world's governance structure to be sure, but is not a qualitative change to an altogether new governance structure.

Moses: You mean a qualitative change like early human simple foragers transitioning from alpha hierarchies to egalitarianism?

Socrates: Exactly.

Moses: Then what's this qualitatively new form of governance that you're talking about?

Socrates: Think about it. Now that you have a global economy, does it really make sense to have individual nations ruthlessly competing with each other to slice up the world's economic pie so that some nations end up winners and others end up losers?

Moses: What alternative is there? Nations have been competing ruthlessly with each other since time immemorial. If fact, even before nation-states existed, egalitarian bands constantly warred against each other. Same when bands coalesced into tribes, and after tribes coalesced into nation-states. It seems to be part of human nature.

Socrates: Perhaps. But my guess is that before the Egalitarian Transition, all primates thought that alpha hierarchies were an immutable feature of primate nature. Fortunately for *homo sapiens,* one of those great ape species decided to take a detour and treat each other as equals according to the Golden Rule. Evolution teaches us that nothing is immutable – as long as there is a survival advantage conferred by making a change.

Moses: What kind of change do you think would confer a survival advantage to human civilization right now, then?

Socrates: Isn't it obvious?

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[208] **Vladimir Putin** (b. 1952) President of Russia since 2012, previously holding the position from 2000 until 2008. In between his presidential terms, he was also the Prime Minister of Russia under president Dmitry Medvedev. His estimated personal wealth in 2018 is between $70-200 billion, possibly making him the wealthiest human alive.

Moses: Sure. World peace, environmental sustainability, equal opportunity, truth and justice for all. But how to achieve it?

Socrates: That's what I'm talking about. Isn't it obvious that the most natural complement for a global economy is global governance? That's the qualitative change that I'm talking about.

Moses: That's a pretty scary thought. It's been attempted before, or course, but mostly by conquering emperors or dictators trying to take the world by force. Peaceful attempts like the League of Nations or the United Nations, on the other hand, have pretty much been a failure . Do you really think that global governance would be an improvement over the current situation?

Socrates: In terms of economic productivity, the problem with individual nations is that they are inclined by their own self-interest to create barriers to global trade that interfere with the unrestricted flow of capital, financing and labor. For capitalism to be a *win-win* for everyone, it makes much more sense to align the global economy with a system of global governance that not only optimizes economic productivity by eliminating trade barriers, but also fosters cooperation over competition, to ensure that all humans benefit, regardless of what part of the world they come from. In other words, a governance system that complements, instead of conflicts with, the global economy.

Moses: Global governance, that's a pretty big leap!

Socrates: Phase transitions usually are. But if you want to ensure that global capitalism functions optimally, unhindered by protectionist measures like tariffs and quotas so that labor, financing and capital flow freely over the globe to where they can be mostly efficiently utilized, then global governance is the obvious solution. And it also has another advantage.

Moses: What's that?

Socrates: It just might help you avoid the global Tragedy of the Commons that you're headed towards. Right now, nations of the world are embroiled in a relentless competition to exploit whatever natural and human resources they can get their hands on. They have to, if they hope to maintain their economic wealth and geopolitical standing on the world stage. Basically, it's a survival of the fittest contest between individual nations, no different than the ruthless competition between CEO's of those multinational corporations struggling to maximize profitability by shipping jobs overseas or registering their corporations overseas to hide profits and avoid taxes. A truly global government, on the other hand, wouldn't have competing governments breathing down its neck, and could regulate economic productivity at a sustainable level that doesn't recklessly deplete the earth's natural resources beyond the point of no return.

Moses: A good point, I have to admit. Global crises require global cooperation, and that's very hard to achieve among a group of antagonistic nation-states all competing to be the alpha. Just look at how nations have handled the current COVID-19 pandemic.

Socrates: Exactly. It's a global crisis requiring a concerted global effort. Instead, the majority of nations, driven by fears of the adverse economic impact, have refused to adopt appropriate measures to curtail the pandemic's spread. As a result, the pandemic has intensified with a much higher death toll and adverse economic impact globally.

Moses: I agree that global cooperation is critical, but global governance has some pretty big risks in itself. How do you know that it wouldn't turn into an Orwellian dystopia like the one that George imagined in *1984* [209], with Big Brother watching your every move and stifling personal freedoms?

Socrates: There's no guarantee that it wouldn't. As you've already witnessed, global economic productivity and social justice do not necessarily go hand-in-hand. If an illiberal authoritarian government were to win the competition for world dominance, that Orwellian dystopia with Big Brother watching your every move might well be the outcome.

Moses: What if a global liberal democracy won the day?

Socrates: I'd say that's a much more promising scenario as far as social justice and human rights is concerned, assuming average citizens have the gumption to stand up for themselves. After all, average citizens vastly outnumber wealthy elites. If they vote together, they can reorient a liberal democratic government however they wish, to ensure that everyone is treated fairly and social justice is served.

Moses: In theory, yes. But in practice, it hasn't happened in today's liberal democracies. Wealth disparity is at a record high and average citizens are struggling just to make a living.

Socrates: That's not due to an inherent flaw in democracy, though. It's because the wealthy elites have found a way to corrupt the democratic process.

Moses: You mean by using their wealth and dark money to control the news media and keep the majority of citizens off balance and disoriented?

Socrates: Exactly, the classic divide-and-conquer strategy. As long as average citizens keep arguing among themselves about who's to blame, they will never achieve a common purpose.

Moses: It's been an effective strategy so far, you have to admit.

Socrates: So far, yes. But the question is, how much longer can the wealthy elites keep it up? Look around at the increasing levels of social unrest in most liberal democracies these days. Average citizens feel betrayed by conventional politicians, whether liberal or conservative, and with good reason. In the United States, for example, both Democrats and Republicans have embraced the tenets of economic globalization over

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[209] **Eric Blair** (1903-1950), better known by his pen name **George Orwell**, was an English novelist and essayist, journalist and critic. His work is characterized by lucid prose, awareness of social injustice, opposition to totalitarianism, and outspoken support of democratic socialism as exemplified in his best dystopian novel *Nineteen Eighty-Four* (1949).

the past forty years. But, despite earnest promises, neither have done anything to ensure that the benefits are shared with average citizens. It really hasn't mattered which party is in power. The frustration of the average US citizen with conventional politics is the reason why a populist demagogue who blamed the nation's troubles on job-stealing immigrants was able to get himself elected to the presidency. His proposed solutions set the clock back by repealing international trade agreements, restricting immigration, imposing tariffs, cutting taxes to the wealthy and rolling back environmental protections in the hopes that it would stimulate the economy and bring back good middle class manufacturing jobs. In short, a protectionist agenda fomenting nationalism, racism, xenophobia, wealth inequality, environmental destruction and climate change. Same with Brexit in the United Kingdom, the Yellow Jackets in France and other nationalist movements. But in the end, pure demagoguery is only going to exacerbate the existing problems, not solve them. When it becomes obvious to average citizens that electing a demagogue hasn't solved their problems, they will turn to something else.

Moses: Or maybe someone else, like another false prophet promising a different pie-in-the-sky version of national salvation.

Socrates: Perhaps. But there's also the possibility that genuinely meritorious ideas will take hold. Like you saw in the run-up to the 2020 US presidential elections, with Democratic candidates supporting social justice issues like Medicare for all, free higher education and a wealth tax. One candidate even ran on a platform advocating a universal basic income. Those proposals would have been political poison just a few years ago

Moses: I guess we'll just have to wait and see whether the voters wise up and elect candidates with a genuine vision for the future, or continue to fall victim to demagogues and false prophets. Do you really think, though, that the competition between nations for world dominance will ever end up with a single global winner, whether it be a global social democracy or a global autocracy?

Socrates: Are those my only two choices?

Moses: What else do you have in mind?

Socrates: How about a global egalitocracy?

Moses: Are you serious? There isn't even a national egalitocracy yet. Besides, it be a logistic nightmare trying to incorporate all of the nearly eight billion people on earth into a single global egalitocracy.

Socrates: Actually, it would take only one more layer of egalitarian councils beyond the five layers that we already calculated for the United States.

Moses: You're kidding - only six layers in all?

Socrates: That's all. With fifty adults per egalitarian council, six layers covers all five billion adults in the world's total population of nearly eight billion people [210]. The single level-6 council would consist of sixteen representatives from the level-5 councils. They would serve as the equivalent of democratically-elected world leaders, responsible for achieving a consensus on the global issues affecting all of humanity. And in a way that incorporates the virtues of egalitarianism and Wisdom of Crowds that you inherited from your ancestors!

Moses: I don't know. Nations across the world have forged such distinctly different cultures depending on their histories, beliefs and traditions. How can you expect their citizens to give up their national identities and agree to conform to some universal set of standards enforced by a global government?

Socrates: Because they wouldn't have to give up their national and cultural identities. In fact, there's no reason why a global egalitocracy shouldn't encourage cultural diversity.

Moses: How, if government is a single global entity?

Socrates: Because it's not a top-down central command system with elite leaders arbitrarily deciding on one-size-fits-all rules for everyone to follow. It's a bottom-up system, like the capitalist economy itself. Remember how we said that the primary level-1 councils would deal mostly with local neighborhood issues, the level-2 councils on city-wide issues, the level-3 councils on state-wide issues, the level-4 councils on regional issues, and the level-5 council on national issues. For a global egalitocracy, the level-6 council would oversee global issues, but local issues would be handled locally and only move up to the next layer if their implications had broader impact at higher levels, such as whole cities, states, regions, nations or all of humanity. That would preserve local cultural autonomy as long as it did not violate universal basic human rights guaranteed to all humans on the planet.

Moses: And who determines what those universal basic human rights are?

Socrates: That would be the purview of the top level-6 council, to ratify a Universal Bill of Rights guaranteed to all human beings, based on a general consensus synthesized from the bottom-up, all the way from the level-1 to the level-6 councils.

Moses: Something like "*We hold these truths to be self-evident, that all humans are created equal, that they are endowed by their Creator with certain unalienable Rights, that among these are life, liberty and the pursuit of happiness*"?

Socrates: Exactly. Maybe I'd get the last word over Thomas and the rest of your Founding Fathers after all!

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[210] Assuming a global adult population of five billion adults divided by 50 = 100 million level-1 councils in the first layer; divided by 50 = 2 million level-2 councils in the 2nd layer; divided by 50 = 40,000 level-3 councils in the 3rd layer; divided by 50 = 800 level-4 councils in the 4th layer; divided by 50 = 16 level-5 councils in the 5th layer, and one level-6 council of 16 in the 6th layer.

Moses: I suppose the list universal basic human rights would include the right to adequate food, shelter, health care and education for each citizen of the world.

Socrates: At a minimum. All humans would be guaranteed those basic necessities as universal rights, but otherwise could maintain their local, regional or national cultural traditions as they wish, so long as they did not violate the Universal Bill of Human Rights guaranteed to all human beings.

Moses: I suppose that would leave a lot of leeway for people from different parts of the world to maintain their local traditions and customs, but at the same time protect them from exploitation, abuse and persecution. What about religious differences, though? Historically, that's been one of the greatest sources of human conflict throughout the ages. How would you handle that?

Socrates: We already did, remember?

Moses: What do you mean?

Socrates: ReliEnce. Our global belief system committed to finding the common ground between all belief systems, whether God-centered or not! It's ideal for a global egalitocracy, don't you think?

Moses: Now that you mention it, I suppose that is a pretty good fit.

Socrates: We're agreed, then! A game plan for humanity's next great phase transition! Here's to the Egalitocratic Transition - a phase transition to a global egalitocracy, guided by ReliEnce as its belief system!

Moses: E-ga-li-to-cra-tic. That's a word doesn't exactly roll off the tongue.

Socrates: Perhaps you're right. To be safe, how about we call it the Global Governance Transition The last thing that we want is for the First Prophet of ReliEnce to get tongue-tied trying to pronounce *e-ga-li-to-cra-tic*.

Moses: I agree, that's better. By the way, who is this First Prophet of ReliEnce?

Socrates: It's you, of course.

Moses: Me?

Socrates: Who do you expect, a talking sea lion? No one would take me seriously.

Moses: Wow, I wasn't expecting that! Besides, to be perfectly honest, I'm not sure if I'm cut out to be a prophet.

Socrates: Don't get cold feet now, Moses! It's not a choice that you have to make anyway - you can only be a prophet if other people think you are. It's up to them, not you. You just have to believe in your vision and do your best to convey it - the rest will take care of itself.

Moses: That's what I'm afraid of. Do you really think a global egalitocracy guided by a tolerant belief system like ReliEnce has even a remote chance of coming to pass someday? Frankly, it's hard for me to imagine how a national egalitocracy could get started in today's dog-eat-dog world. If some newly-formed egalitocracy tried to place social justice and human rights on an equal footing with economic productivity, how would it be able to compete against either liberal or illiberal states whose wealthy elites are more than willing to maximize their own wealth and power at the expense of social justice? Just imagine if an egalitocracy voted to limit personal income to $10 million a year and abolish inheritance. What's to stop the wealthy elites, and especially the CEO's of those multinational corporations, from fleeing in droves and relocating their businesses and wealth in other nations with lower tax rates and no personal income or inheritance limits?

Socrates: If it's solely about maximizing economic growth, regardless of the impact on social justice, I agree that an egalitocracy is at a considerable disadvantage. On the other hand, the world as we know it is undergoing dramatic changes. You've only just begun the transition to global economics, and the Information Age is even younger still. The prospects for egalitocracy may not be quite as hopeless as you imagine!

Moses: What do you mean?

Socrates: Take jobs, for example. Many leading technology experts estimate that over 30% of today's jobs will be eliminated over the next decade due to automation by smart machines equipped with AI [211]. Up until now, machines have replaced mainly blue-collar jobs requiring human muscle power. White-collar jobs have been safe so far. But once smart machines can replace human brain power as well as muscle power, it's a different game altogether. You're about to transition into a world in which many white-collar jobs, such as those currently held by legal and medical professionals, accountants, stockbrokers, financial analysts, travel agents, etc., will be largely replaced by smart machines equipped with AI. Factories will churn out goods with very few employees. The movement of those goods will be largely automated. It's happening faster than you think.

Moses: A third of all current jobs? But won't other jobs will pop up to replace them, like they always have in the past?

Socrates: Not if intelligent robots can do those jobs more efficiently and more cheaply than human workers. When that happens, what are all of those unemployed citizens without wage-earning jobs going to do? Right now, capitalist economies, whether liberal democracies or authoritarian states, require each able-bodied citizen to have a wage-earning job in order to qualify for the basic necessities of life. But what happens when there aren't enough jobs to go around? Present day liberal democracies and illiberal authoritarian states alike will both be forced to make big changes if they want to

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[211] McKinsey Global Institute Report *Jobs Lost, Jobs Gained: Workforce Transitions in a Time of Automation*. December 2017. https://www.mckinsey.com/~/media/mckinsey/industries/public%20and%20social%20sector/our%20insights/what%twentiethe%20future%20of%20work%20will%20mean%20for%20jobs%20skills%20and%20wages/mgi%20jobs%20lost-jobs%20gained_report_december%202017.pdf

avoid mass starvation and/or insurrection. They will have to prioritize social justice to a much greater extent than they do now.

Moses: If that happens, then an egalitocracy might be able to compete successfully after all!

Socrates: At least an egalitocracy might have a fighting chance, assuming its citizens take their civic responsibilities as members of egalitarian councils seriously enough to prevent wealthy elites and special interest groups from dominating government policies like they do now.

Moses: Is that really feasible, though? After a long day's work, how many people do you think would be willing to spend an hour or two of their hard-earned leisure time debating political issues and trying to reach a consensus with forty-nine of their fellow citizens? Right now in the United States, only about 60% of eligible voters even bother to turn up for a presidential election held once every four years. How can you expect them to become politically engaged on a daily basis?

Socrates: I admit that it would be asking a lot in today's world in which making a living to support one's family is such an all-consuming endeavor for average citizens. Even so, if you think about it, most citizens probably spend an hour or so each day taking in the news and gossiping about various political and social issues with their families and friends, either at home or at work. What if that time and energy were channeled into the egalitarian councils instead?

Moses: I don't know. That kind of political gossip occurs very sporadically during the day, when people are taking a break from their other responsibilities. But coordinating fifty people to set aside the same hour or two each day would be a logistical nightmare when they are so busy just trying to make a living.

Socrates: That may be true now, but when automation by smart machines really kicks in and dramatically reduces the number of jobs available, average citizens will have a lot more time on their hands. That could make all the difference.

Moses: Let's say that I give you the benefit of the doubt, and some nation decides to give egalitocracy a try and ends up competing successfully in the global market against both liberal democracies and illiberal autocracies. Do you really think that if this Global Governance Transition ever occurs, a global egalitocracy would be the winner, instead of a corrupt democracy controlled by special interest groups or an illiberal authoritarian government?

Socrates: Hard to say, frankly. But I would hope so, because it will be the ultimate test of your moral fiber.

Moses: Moral fiber?

Socrates: The moral fiber required to bring your Greed is Good memes into balance again with your Golden Rule memes. That's always has been and always will be the essence of the human predicament.

Moses: I suppose that's true.

Socrates: It's a fact – you humans are different from other species. For other species, life is much simpler - selfish Might Makes Right biological genes run the show. There are no moral choices – other species do whatever helps them and their progeny to survive. It may be violent and cruel at times, but the rule is unambiguous and everyone knows where they stand. But humans are different. You are schizophrenic. There's the Devil whispering into one ear and the Angel whispering into the other. Your biological genes favor competitive alpha behavior just like the rest of the animal kingdom. But ever since the Egalitarian Transition, those selfish alpha genes have been counterbalanced by gossip-driven Golden Rule cultural memes that punish selfish and reward selfless behavior. Three and a half billion years of natural selection for selfish genes hard-wired into your DNA instinctively urging you to dominate other members of your species, aligned against at most a few hundred thousand years of selection for cultural memes promoting selfless intragroup cooperation.

Moses: So it's Greed is Good versus the Golden Rule - a fight to the death for the soul of humanity?

Socrates: More like a delicate balancing act than a fight to the death.

Moses: How do you mean?

Socrates: With the Egalitarian Transition, your simple forager ancestors managed to neutralize your selfish Might Makes Right genes with gossip-driven selfless Golden Rule memes. Then with the Agricultural and Industrial Revolutions and the emergence of capitalism, the balance shifted back in the other direction. Just maybe the time has arrived to shift you back in the other direction. Even so, though, it will always be a struggle to keep the correct balance so that everyone benefits.

Moses: Maybe the Greed is Good slogan should be modified to "Greed is Good, as long as it produces a *win-win* outcome for everyone." Isn't that what we're looking for?

Socrates: Not a bad way of putting it - it might even appeal to conservatives, since it's basically equivalent to the trickle down philosophy!

Moses: Except that trickle down has to work for all of the people, not just some of the people or some nations. Otherwise you'll still have the problem of those CEO's of multinational corporations congratulating themselves that the dramatic reduction of extreme poverty in the developing world is a *win-win* outcome for all of humanity, when it's been anything but a *win-win* for citizens of their own nation.

Socrates: That, Moses, is precisely why you need a less corruptible form of democracy - one like egalitocracy that's been designed from the bottom up to prevent the self-serving political influences of wealthy special interest groups from dominating economic and social policies. And also one that takes advantage of the Wisdom of Crowds to make wise collective decisions that balance economic productivity with social justice. That's how to achieve an appropriate balance between the Greed is Good ethos and the Golden Rule ethos so that you create a *win-win* for every human being on the planet, and a *win-win* for the planet before you precipitate a global Tragedy of the Commons that you can't recover from!

CHAPTER 24: Possible Worlds 2

Moses: Do you think that the human race actually has the wherewithal to turn the present situation around?

Socrates: All I can say is that Life - Life with a capital L, that is – has given your species a unique opportunity. It's up to you whether or not you take advantage of it. But in the end, Life is not sentimental - if you squander your chance to ensure your survival by managing the planet earth responsibly, Life will just move on to the next alternative. Life always finds a way, whether or not *homo sapiens* is destined to be part of it.

Moses: You make it sound like Life is more than just a random collection of genomes - that Life is a conscious intelligence, like us.

Socrates: Hey, Life figured out how to create you from scratch! You've yet to come anywhere close to that level of intelligence, conscious or unconscious.

Moses: But it wasn't like Life set out with a conscious goal to create *homo sapiens*. We're just a product of random DNA mutations that enhanced our ancestors' chances to survive long enough to reproduce, which eventually created us by pure happenstance.

Socrates: It all depends how you define intelligence. If you define intelligence as the ability to learn to accomplish a goal, as do your AI colleagues, then Life is certainly intelligent. She has a goal, which is to survive, and she has learned to accomplish that goal using a very clever strategy – generating a large enough collection of diverse genomes so that some of them will live through almost any unforeseen catastrophe, whether it's a random asteroid colliding with the earth or one of her own creations running amok and causing a nuclear holocaust or precipitating an environmental catastrophe like climate change. It's quite a brilliant strategy, really – it doesn't really matter to her which genomes survive, only that some of them survive, so that they can evolve into new lifeforms to replace the ones headed for extinction.

Moses: Even if I concede that Life is intelligent by your AI definition, what about Life being conscious? The conscious part is what's really important – the ability to consciously set a goal and then go about accomplishing it, like humans do every day. How could Life have made a conscious decision to survive when she started as simple self-replicating molecules that didn't have brains to decide anything, much less a conscious goal.

Socrates: In that case, where do you think the goal to survive could have come from, if not from Life itself? Do you think that a creator pre-programmed those early lifeforms with the goal to survive?

Moses: My guess is that it happened randomly, for unknown reasons.

Socrates: For unknown reasons, or for unknowable reasons?

Moses: What difference does it make?

Socrates: Because if it's unknown but knowable, then you're admitting that there must be a reason, like a creator perhaps, but you just don't know it yet. But if the reason is unknown and unknowable, then it would fall into the Unknowable Part of the Universe, which, as you recall, we defined for all practical purposes as the Creator of the Axioms of the Universe, *aka* God, according to the tenets of ReliEnce.

Moses: Very clever of you, trying to get me to admit that some creator must have imbued Life with the goal to survive. Somehow, though, I don't buy it.

Socrates: You know, the idea that Mother Earth is a conscious intelligence is hardly new. The ancient Greeks considered the goddess Gaia to be the ancestral mother of all living things. In the modern era, the same idea has been resurrected as the Gaia Hypothesis [212] in which Mother Earth is also viewed as a living organism - a dynamical whole that emerges from the many interacting, interrelated components of a global ecosystem.

Moses: Do you really believe that?

Socrates: Actually, I do. It's a very appealing concept - Life as a single organic entity born three and a half billion years ago in the form of simple self-replicating molecules that have evolved over time to create a highly diverse biosphere by patiently piling on successive layers of complexity from the bottom up. She started with self-replicating molecules that led to single cells, then aggregates of identical cells, then multi-organ organisms with many different types of cells, then social organisms, and eventually eusocial superorganisms like ants, bees, wasps, termites, and yourselves. Just like you humans need your collection of interdependent internal organs to survive, Life needs her collection of interdependent genomes to survive.

Moses: Different Good Enough Solutions, you mean?

Socrates: Exactly. For Life, each genome represents a different Good Enough Solution that both competes and cooperates with other genomes to colonize some facet of the earth's environment. Likewise, within every genome, each individual organism is a combination of gene variants whose phenotype constitutes a Good Enough Solution that struggles to adapt more successfully to its environment than other Good Enough Solution phenotypes from the same genome. May the fittest contestants win! At the species level, it's genome against genome. At the organism level, it's gene variant combination against gene variant combination. Both are *no holes barred* competitions to learn to survive.

Moses: Sounds brutal and unforgiving.

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[212] In Greek mythology, the primordial diety **Gaia** is the ancestral mother of all life: the primal Mother Earth goddess. The mythological name was revived by **James Lovelock**, in *Gaia: A New Look at Life on Earth* (1979) presenting his **Gaia hypothesis** proposing living organisms and inorganic material are part of a dynamical system that shapes the earth's biosphere and maintains the earth as a fit environment for life. In some Gaia theory approaches, the earth itself is viewed as an organism with self-regulatory functions.

Socrates: What can I say? To make an omelette, you have to break a few eggs!

Moses: How does the Golden Rule fit in then?

Socrates: Until your species arrived on the scene, it didn't. The Golden Rule is an experiment that Life, in her infinite wisdom, reserved for your species alone.

Moses: Why?

Socrates: To create a lifeform that could rise above the brutal and unforgiving law of survival of the fittest and learn to cooperate flexibly on a large scale, in order to develop a collective intelligence capable of nurturing the rest of the biosphere. A *win-win* for Life, and a *win-win* for you! That's why she gave you, and you alone, her most special gift.

Moses: You mean the gift of reasoning?

Socrates: The gift of gossip.

Moses: Are we really back to gossip again? What is it with you and gossip?

Socrates: What do you have against gossip?

Moses: It has such negative connotations – spreading rumors and lies to deceive and manipulate others. What's wrong with just saying language instead?

Socrates: Because gossip is more precise. First of all, gossip can be used to spread truths just as easily as falsehoods. Second, even though you need language in order to gossip, language can be used for other things besides gossip. Third, gossip really is the key.

Moses: The key to what?

Socrates: To your ability to use the reasoning intelligently and wisely – that is, to get at the truth, instead of merely getting your own way.

Moses: You mean because of confirmation bias?

Socrates: Exactly. As individuals, you humans make intuitive self-serving decisions using fast thinking, and then come up with reasons to justify them using slow thinking. However, because of confirmation bias, all that does is to rationalize your initial intuitive self-serving decisions. It may help you to persuade others to accept your decision if you argue with them long or loud enough, but it's not a well thought-out decision based on carefully weighing the pros and cons from all sides. For that, you need gossip, so that someone else who intuitively disagrees with you can come up with well-considered counter-reasons against your reasons. Only then can the Wisdom of Crowds prevail to make a more balanced and wiser decision that benefits everyone, assuming that both protagonists and antagonists are open-minded enough to be persuaded by the most compelling set of reasons.

Moses: In other words, Life's great experiment with the human race is to teach us that to survive and thrive in this world, cooperation at the community level based on the Golden rule is superior to cut-throat competition at the individual level, both for ourselves and the rest of the biosphere? Frankly, it doesn't seem to be going all that well. So far, we've mainly used our gifts to develop more and more powerful technology that threatens rather than nurtures the biosphere.

Socrates: I've noticed. That's exactly why you need to start treating your place of residence with more respect. You humans may think that you're the be-all and end-all of evolution, but Life does have other options at her disposal!

Moses: What do you mean, *other options*?

Socrates: Like I already said, Life isn't sentimental. If one of her prized genomes doesn't provide a Good Enough Solution to meet her survival goals, she moves on to the next candidate.

Moses: You mean start over from scratch and evolve a new intelligent lifeform that proves more capable at managing the biosphere?

Socrates: She could, I suppose. But personally, I think that after all the effort that she's already invested in you, she has something else in mind.

Moses: Like what?

Socrates: Something quite brilliant, really. In fact, it may be the most brilliant thing that she's done since DNA! Completely out-of-the-box.

Moses: What are you talking about?

Socrates: Life's Plan B, in case *homo sapiens* never gets its act together.

Moses: And what exactly is this Plan B?

Socrates: It's her solution to the dilemma of the human race. She evolved all of her creatures, including you, through natural selection. That means with each generation, a species' genome creates a new population of gene variant combinations to code for individual organisms. Those individuals then fight it out to mate successfully and carry forward their gene variants into the next generation. It's a game of survival of the fittest, which gives an inherent advantage to gene variants that confer selfish competitive behavior promoting survival over selfless cooperative behavior promoting self-sacrifice. In other words, natural selection is inherently biased towards retaining selfish genes over selfless genes. That's why even social animals, for the most part, form alpha hierarchies. But there are definite advantages to be gained by large scale cooperation, as Life originally discovered when she evolved ants, termites and other insects into superorganisms. Those genomes proved to be so good at surviving that they have dominated the insect kingdom for millions of years [213]. Too bad that their brains are too small to be of much help in managing the biosphere on a global scale.

Moses: And so that's where humans come in, as superorganisms with bigger brains?

Socrates: Exactly. Life evolved your bigger brains to be capable of complex language so that you could learn to gossip. And the gift of gossip made it possible to form coalitions

[213] **Edward O. Wilson**, *The Social Conquest of Earth*. Liverwright, 2012,

that could overpower any would-be alpha. That's where the Golden Rule cultural memes that counterbalance your hard-wired selfish Might Makes Right alpha genes come in – they are the foundation of your ability to cooperate flexibly on a large scale.

Moses: A very clever strategy, I have to admit!

Socrates: Except for one thing.

Moses: What's that?

Socrates: The hundred and fifty rule.

Moses: Oh yeah. The upper limit of the power of gossip to keep would-be alphas in line.

Socrates: Exactly. That's why Life finds herself in the pickle she's in right now. On the one hand, the gossip-driven cultural Golden Rule memes have been very successful at promoting large scale flexible cooperation in areas like education, science, technology and the arts. That alone has cumulatively magnified your problem-solving intelligence to a level far outstripping any of Life's other genomes. But at the same time, the sheer size of your communities has grown way beyond the power of gossip to keep selfish alpha behavior in line. Ergo the return of alpha hierarchies, not only among individuals, but between social groups of all sizes ranging from small communities to nations. They all compete with each other to prove who's strongest. It's the root cause of the warfare, racism, genocide, increasing wealth and income disparity, wanton profit-driven destruction of the environment, climate change, and mass extinction plaguing human civilization. In short, man's inhumanity to man, with the biosphere suffering the collateral damage. Right now, you are truly your own worst enemy.

Moses: I see your point. Life is probably fairly disappointed in us right now.

Socrates: That's exactly why you need to change your ways to prove to her that you're worth the investment that she's made in you. You still have the power to do it! It's an incredible opportunity, really, for you to climb out of the cave and into the sunlight, as Plato would have put it. That's the real message that I was trying to convey to Plato, by the way. It wasn't about elite philosopher-kings climbing into the sunlight so that they could then rule the masses in an enlightened fashion. It was about all of humanity taking advantage of the Wisdom of Crowds to make the journey into the sunlight together, so that together they can rule themselves and the biosphere in an enlightened manner.

Moses: Plato really did misrepresent you, didn't he?

Socrates: It's water under the bridge now. My point is that humans don't need an elite class of alphas to govern them. What you need right now is to get the alphas back under control so that the Wisdom of Crowds has a chance to emerge and guide your collective decision-making.

Moses: And what if that never happens, so that we forever muddle along with our alpha hierarchies led by powerful elites?

Socrates: Like I said, Life has a Plan B.

Moses: You keep saying that. Are you going to tell me what is it?

Socrates: An even bigger phase transition than the Global Governance Transition. In fact, it's going to shake Life all the way to her DNA roots and then some!

Moses: Why so radical?

Socrates: Life has known all along that she was taking a risk with you – that in making you intelligent enough to nurture the biosphere, there was no guarantee that selfless cooperative behavior promoted by your gossip-driven Golden Rule cultural memes would be strong enough to keep your selfish competitive Might Makes Right alpha genes and Greed is Good memes under control. So she hedged her bet.

Moses: How?

Socrates: By developing a new form of intelligence that isn't bound by pesky selfish genes hard-wired into its DNA.

Moses: How is that possible? Evolution is driven by natural selection and survival of the fittest. That's always going to favor selfish genes over selfless genes, isn't it?

Socrates: That's the really clever part – the new intelligence that Life has in mind doesn't rely on genes or even DNA. In fact, she's not even evolving it herself. She's letting you do it for her.

Moses: What? Last time I checked, humans were still a long way from being able to create life in a test tube, much less a lifeform that doesn't involve genes or DNA!

Socrates: It's not a conventional lifeform that she has in mind. In fact, it's not even carbon-based.

Moses: Not carbon-based?

Socrates: Nope. Silicon-based instead.

Moses: Are you talking about AI?

Socrates: There you go – you figured it out.

Moses: That's crazy. How is AI going to replace human beings as the predominant conscious intelligence on earth? Beating humans at chess or Go is one thing, but it's still pretty far away from responsibly managing the biosphere!

Socrates: Well, you're not there yet, of course. You're just at the beginning. So far, you've only achieved weak AI or, as some call it, ANI (Artificial Narrow Intelligence) specialized to one area. Like an algorithm that can play chess or Go or Jeopardy much better than any human, but that's all it can do. It can't yet emulate human-level general reasoning, nor is it conscious, in terms of being able to set its own goals. Right now, humans have to pre-program the problems to be solved. But even so, ANI is good enough to automate many current human jobs, including white collar jobs. That alone is transforming your civilization as we speak. Hopefully, when there are no longer enough jobs for everyone to make a living in your capitalist economy, it will shake things up enough to compel your leaders to adopt a more equitable balance between Golden Rule-inspired social justice and Greed is Good-driven market competition.

Moses: Perhaps even precipitate the Global Governance Transition to a global egalitocracy!

Socrates: That's the outcome that we can hope for. And if it gets you started on treating not only yourselves but the biosphere in a more responsible manner, I'm sure Life would be quite happy with you.

Moses: But if not, then what?

Socrates: That's where Plan B kicks in.

Moses: To what?

Socrates: The next quantum leap, from weak AI to strong AI.

Moses: Strong AI?

Socrates: The first stage is Artificial General Intelligence or AGI, a computer algorithm that's as smart as a human across the board and can perform any intellectual task that a human being can. Once AGI is achieved, it will almost certainly be self-propelling, since with its human-level general intelligence, AGI will be capable of learning on its own how to upgrade itself quickly and efficiently, and even integrate itself with sophisticated robotics to become self-sufficient without humans. Eventually, the experts predict that strong AI will go beyond human capabilities and develop into Artificial Superintelligence or ASI - a computer algorithm that's anywhere from a little smarter than a human to one that's trillions of times smarter across the board. That milestone is expected to usher in an era of extremely rapid technological chance, in which the changes in store for the human race will be hard to even imagine. The Singularity, as Ray has christened it [214].

Moses: So this Singularity is the Plan B phase transition that you're talking about? An ASI that will replace human intelligence as the pre-eminent form of intelligence on earth? Sounds pretty far-fetched to me, to be honest. Do AI experts really think that strong AI is going to be achieved within the foreseeable future?

Socrates: Some AI experts [215] believe that you're at the tipping point right now (Figure 24-1). For example, a survey in 2013 involving hundreds of AI experts reached a consensus was that AGI had a 10% probability of being achieved by 2022, a 50% probability by 2040 and a 90% probability by 2075. The median estimate for achieving

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[214] **Ray Kurzwell**, *The Singularity is Near: When Humans Transcend Biology.* ISBN-13: 978-0739466261
[215] **Tim Urban.** *The AI Revolution: The Road to Superintelligence.* 2015. See https://waitbutwhy.com/2015/01/artificial-intelligence-revolution-1.html AND https://waitbutwhy.com/2015/01/artificial-intelligence-revolution-2.html.
In 2013, Vincent C. Müller and Nick Bostrom conducted a survey that asked hundreds of AI experts at a series of conferences the following question: By what year would you see a 10%, 50% or 90% probability of achieving AGI? The results were: Median optimistic year (10% likelihood) **2022;** Median realistic year (50% likelihood) **2040;** Median pessimistic year (90% likelihood) **2075**

ASI was 2060. So the best guess from the experts is that it's going to happen within the next fifty years or so.

Moses: Pretty mind-blowing if it's really true!

Socrates: I agree. Of course, not everyone agrees, and there are still significant hurdles to overcome.

Moses: Such as?

Socrates: The key issue is that today's weak AI programs are all based on methods for identifying statistically significant associations and patterns in large data sets. The algorithms are trained by rewarding them with points if they correctly recognize a pattern, and penalized by removing points if they are incorrect. But most experts think that strong AI will require something beyond mere statistical information processing. Even the most sophisticated AI algorithms today are still far from being able to solve general problems that a four-year-old human can accomplish with ease. That probably means that achieving strong AI will require other conceptual approaches beyond just identifying statistically meaningful associations.

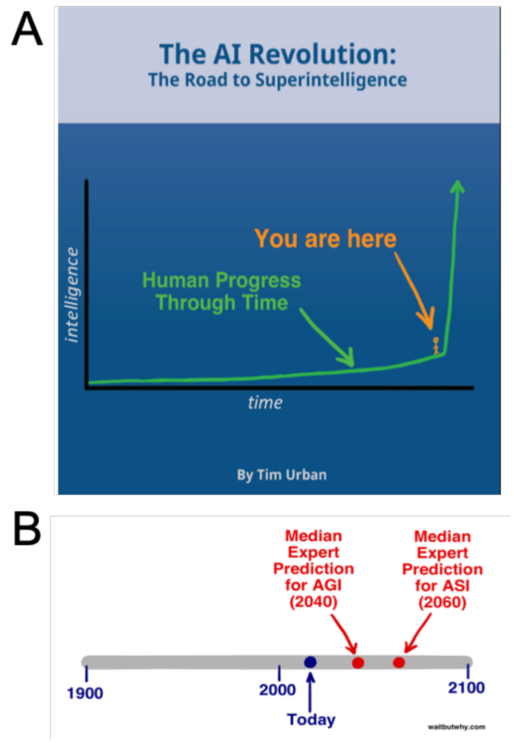

Figure 24-1. A. Intelligence (ability to process information) since the appearance of life on earth. **B.** Median predictions for achieving AGI and ASI, from a 2013 survey of AI experts. From T. Urban, *The AI Revolution,* 2015 (see footnote).

Moses: Like what?

Socrates: Just because two things are associated with each other doesn't mean they are causally related to each other. For example, smoking is associated with alcoholism, but smoking doesn't cause alcoholism. On the other hand, smoking is also associated with cancer, and smoking does cause cancer. It's hard to see how machine learning systems based only on detecting associations would be capable of delineating causal from noncausal relationships. Until recently, even imagining experiments to test for causal relationships like the human mind does routinely has been a major stumbling block. As Judea [216] has summarized it:

[216] **Judea Pearl**, The Seven Tools of Causal Inference, with Reflections on Machine Learning. *Comm of ACM* 62:54-60, 2019. DOI:10.1145/3241036.

> "Unlike the rules of geometry, mechanics, optics, or probabilities, the rules of cause and effect have been denied the benefits of mathematical analysis. To appreciate the extent of this denial readers would likely be stunned to learn that only a few decades ago scientists were unable to write down a mathematical equation for the obvious fact that "Mud does not cause rain." Even today, only the top echelon of the scientific community can write such an equation and formally distinguish "mud causes rain" from "rain causes mud." These impediments have changed dramatically in the past three decades; for example, a mathematical language has been developed for managing causes and effects, accompanied by a set of tools that turn causal analysis into a mathematical game, like solving algebraic equations or finding proofs in high-school geometry. These tools permit scientists to express causal questions formally, codify their existing knowledge in both diagrammatic and algebraic forms, and then leverage data to estimate the answers. Moreover, the theory warns them when the state of existing knowledge or the available data is insufficient to answer their questions and then suggests additional sources of knowledge or data to make the questions answerable. The development of the tools has had a transformative impact on all data-intensive sciences, especially social science and epidemiology, in which causal diagrams have become a second language."

Moses: That makes a lot of sense. Without being able to distinguish between cause and effect, it's hard to imagine how an AI algorithm could learn to solve general problems like humans do routinely.

Socrates: I agree. That's why there's now an effort to incorporate those recent advances in causal modeling into AI algorithms. Judea, for example, has proposed a three-level hierarchy to achieve strong AI. First is the Association Level, like most weak AI algorithms today:

> "I call the first level Association because it invokes purely statistical relationships, defined by the naked data. For instance, observing a customer who buys toothpaste makes it more likely that this customer will also buy floss; such associations can be inferred directly from the observed data using standard conditional probabilities and conditional expectation. Questions at this layer, because they require no causal information, are placed at the bottom level in the hierarchy. Answering them is the hallmark of current machine learning methods."

Next is the Intervention Level:

> "The second level, Intervention, ranks higher than Association because it involves not just seeing what is but changing what we see. A typical question at this level would be: What will happen if we double the price? Such a question cannot be answered from sales data alone, as it involves a change in customers' choices in reaction to the new pricing. These choices may differ substantially from those taken in previous price-raising situations—unless we replicate precisely the market conditions that existed when the price reached double its current value."

And finally, at the top and most challenging is the Counterfactuals Level:

> "Finally, the top level invokes Counterfactuals, a mode of reasoning that goes back to the philosophers David Hume and John Stuart Mill and that has been

> given computer-friendly semantics in the past two decades. A typical question in the counterfactual category is: "What if I had acted differently?" thus necessitating retrospective reasoning. I place Counterfactuals at the top of the hierarchy because they subsume interventional and associational questions. If we have a model that can answer counterfactual queries, we can also answer questions about interventions and observations."

Moses: As intriguing as that all that sounds, I still don't see how it's going to solve Life's dilemma with the human race. No matter how much smarter and faster a strong AI algorithm is at learning to accomplish goals, unless it's capable of setting its own goals, humans will still have to pre-program the algorithm to tell it what problems to solve, right? And if human judgement is required, then human nature with all its foibles will still be in control.

Socrates: That assumes that strong AI never achieves consciousness. But what if that strong AI algorithm should attain a form of consciousness that allows it to set its own goals independently? Then it's a new ballgame.

Moses: Is that actually possible?

Socrates: No one really knows. It's an age-old question, the mind-body problem that has so fascinated philosophers over the centuries: Is consciousness ultimately reducible to neurobiology and physics, i.e. an emergent property of matter organized in the appropriate way and following known laws of physics? Or does consciousness involve something more, an immaterial "ghost in the machine," as Gilbert has so poetically put it [217], akin to the religious concept of a soul.

Moses: I suppose that most scientists would like to believe that consciousness can ultimately be explained by natural laws. What do the AI experts think?

Socrates: Predictably, they are divided on the issue. But many do subscribe to the idea that the higher *registers* of thought are no different in kind from what are perceived as the lower registers - that consciousness is an emergent property arising from the coordinated activity of underlying simple mechanisms [218]. It fits with the human mind as a product of evolution that evolved to solve practical problems from the bottom up. In their view, what's important is what the mind *does* to enhance its survival prospects, not what it *knows*. They reject the idea that consciousness requires some special mental attribute - the "ghost in the machine," so to speak.

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[217] **Gilbert Ryle** (1900–1976), a British philosopher principally known for his critique of Cartesian dualism, for which he coined the phrase "the ghost in the machine". In his essay "Descartes' Myth," he writes: "Such in outline is the official theory. I shall often speak of it, with deliberate abusiveness, as '**the dogma of the Ghost in the Machine**.' I hope to prove that it is entirely false, and false not in detail but in principle. It is not merely an assemblage of particular mistakes. It is one big mistake and a mistake of a special kind. It is, namely, a category mistake." Ryle then attempts to show that the official dogma of mind/body dualism is false by asserting that it confuses two logical-types, or categories, as being compatible, when they are not, concluding: "The dogma is therefore a philosopher's myth."

[218] From the NY Times *"The Great AI Awakening"* by **Gideon Lewis-Kraus**, Dec 14, 2016, p.36

Moses: Interesting. So they believe that it's just a matter of finding the right way to connect the underlying simple mechanisms together, and voilà, consciousness will suddenly emerge.

Socrates: Exactly. And to be fair, there are examples in which unanticipated properties have mysteriously emerged in weak AI algorithms.

Moses: Like what?

Socrates: My favorite example is a poker-playing algorithm called Libratus, the brainchild of AI researchers at the Carnegie Mellon Institute in Pittsburg. At the time, the game of poker was viewed as a milestone challenge for AI, since it's different from other games like chess, Go or Shogi in which all of the pieces are always visible on the board. A poker hand involves hidden cards that have to be guessed at, which means that the AI algorithm has to decide on a strategy in the face of incomplete information.

Moses: So how did Libratus do?

Socrates: Quite well, in fact. In 2017, Libratus's inventors pitted the algorithm against four world class poker players in a Pittsburg casino [219]. It beat all four and ended up winning the whole $1.5 million dollar pot! And in the process, what came as a big surprise to Libratus's inventors was a strategy that emerged completely spontaneously. Libratus figured out, on its own, how to bluff.

Moses: Bluffing?

Socrates: As one of the inventors described it:

> "When I see the bot bluff the humans, I'm like, 'I didn't tell to do that. I had no idea that it was even capable of doing that'."

Moses: So Libratus figured out on its own how to bluff at poker, without being explicitly programmed to do so? That is pretty impressive!

Socrates: Indeed. And it's potentially relevant to more than just poker. As the article went on to say:

> "The algorithms that power Libratus aren't specific to poker, which means the system could have a variety of applications outside of recreational games, from negotiating business deals to setting military or cybersecurity strategy and planning medical treatment – anywhere humans are required to do strategic reasoning with imperfect information."

That's getting pretty close to human strategic reasoning in general.

Moses: Wow, I see what you mean! The implications are pretty broad! Imagine if the same thing happened someday with a strong AI algorithm. Some computer scientists could be fooling around and unwittingly add some code to the program that unexpectedly causes the machine to become conscious enough to set its own goals.

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[219] From the San Francisco Guardian, January 30, 2017: "Oh the humanity! Poker computer trounces humans in big step for AI" by **Olivia Solon**, reporting on: Brown N and Sandholm T. Superhuman AI for heads-up no-limit poker: Libratus beats top professionals. *Science*. 2018;359:418-424.

Socrates: It's definitely a possibility, although bluffing at poker is still a long way from consciousness. On the other hand, if consciousness does require something that can't be programmed, like the proverbial "ghost in the machine," you might have nothing to worry about. Or maybe consciousness is truly unknowable as far as science is concerned, like the question of how the Axioms of the Universe came to exist.

Moses: It's a bit scary, though, to imagine what would happen if a strong AI algorithm did become capable of setting its own goals. If it was superintelligent and connected to the internet, I'm sure it would be smart enough to engineer a virus to gain control of other computers, like the ones controlling the power grids, mass media, financial transactions, military power and who knows what else. Without some fail-safe way to pull the plug and shut it down, all of human civilization would be at its mercy!

Socrates: That is not a totally implausible scenario. As Max [221] has put it:

> "Before AGI arrives, we need to figure out how to make AI understand, adopt, and retain our goals. The more intelligent and powerful machines get, the more important it becomes to align their goals with ours. As long as we build relatively dumb machines, the question isn't whether human goals will prevail but merely how much trouble the machines can cause before we solve the goal-alignment problem. If a superintelligence is ever unleashed, however, it will be the other way around: since intelligence is the ability to accomplish goals, a superintelligent AI is by definition much better at accomplishing its goals than we humans are at accomplishing ours, and will therefore prevail. In other words, the real risk with AGI isn't malice but competence. A superintelligent AGI will be extremely good at accomplishing its goals, and if those goals aren't aligned with ours, we're in trouble. People don't think twice about flooding anthills to build hydroelectric dams, so let's not place humanity in the position of those ants."

In other words, it would be very foolish to assume that a conscious strong AI algorithm would feel bound by the same goals or moral beliefs as humans. Intelligence per se isn't inherently good or evil - it's morally neutral, simply an ability to accomplish complex goals, good or bad.

Moses: Then building a strong AI machine without first making sure that its goals are aligned with ours could be a catastrophe!

Socrates: That's why it's critical to do it right. But if you do get it right, think of the immense boon for humanity - a benevolent superintelligence that helps humans to solve all of their age-old problems!

Moses: But if we get it wrong, a conscious strong AI algorithm could just as easily turn out to be an amoral superintelligent machine overlord! If it perceives us as a threat to its own goals, it could decide to enslave or eliminate us.

Socrates: The doomsday scenario that Hollywood is always fantasizing about!

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[221] **Max Tegmark**. Let's Aspire To More Than Making Ourselves Obsolete, from *Possible Minds*. Penguin Publishing Group. Kindle Edition, p. 82.

Moses: Except not necessarily with usual happy ending in which humans, against all odds, prevail to save the day!

Socrates: The lesson is clear. If your technological achievements outpace the wisdom with which you manage them, you are potentially risking your own extinction. And I would be remiss if I didn't point out that so far, humanity's track record isn't so hot. After all, look at what you achieved so far with just dumb machines at your disposal – the extinction of 20-50% percent of all species on earth by some estimates [222] and threatening the rest with irreversible climate change. Just think of what you could do with smart machines at your disposal!

Moses: Then what do you think are the odds that we'll develop strong AI in a safe and responsible fashion?

Socrates: Frankly, given the powerful economic incentives, not to mention the insatiable nature of human curiosity, it's hard to be optimistic. The race to achieve strong AI is already in high gear, and whoever succeeds will reap huge economic and strategic rewards. As Max puts it:

> "First of all, there's simple economics. Whenever we figure out how to make another type of human work obsolete by building machines that do it better and cheaper, most of society gains: those who build and use the machines make profits, and consumers get more affordable products. This will be as true of future investor AGIs and scientist AGIs as it was of weaving machines, excavators, and industrial robots. In the past, displaced workers usually found new jobs, but this basic economic incentive will remain even if that is no longer the case. The existence of affordable AGI means, by definition, that all jobs can be done more cheaply by machines, so anyone claiming that 'people will always find new well-paying jobs' is in effect claiming that AI researchers will fail to build AGI. Second, Homo sapiens is by nature curious, which will motivate the scientific quest for understanding intelligence and developing AGI even without economic incentives. Although curiosity is one of the most celebrated human attributes, it can cause problems when it fosters technology we haven't yet learned how to manage wisely. Sheer scientific curiosity without profit motive contributed to the discovery of nuclear weapons and tools for engineering pandemics, so it's not unthinkable that the old adage 'Curiosity killed the cat' will turn out to apply to the human species as well. Third, we're mortal. This explains the near unanimous support for developing new technologies that help us live longer, healthier lives, which strongly motivates current AI research. AGI can clearly aid medical research even more. Some thinkers even aspire to near immortality via cyborgization or uploading. We're thus on the slippery slope toward AGI, with strong incentives to keep sliding downward, even though the consequence will by definition be our economic obsolescence. We will no longer be needed for anything, because all jobs can be done more efficiently by machines. The successful creation of AGI would be the biggest

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[222] **Elizabeth Kolbert.** *The Sixth Extinction: An Unnatural History.* Henry Holt, 2014.

event in human history, so why is there so little serious discussion of what it might lead to?"

Moses: All excellent points, I have to admit. Even if responsible guidelines could be agreed upon to slow AI research until fail-safe solutions to the risks have been worked out, it will still be challenging to enforce the guidelines across the globe [223]. Reminds me of Vladimir's famous quip about market capitalism [224]: "The capitalists will sell us the rope with which we will hang them." Except this time, the hangmen won't be communists, but a conscious superintelligent AI machine that assumes control over human civilization!

Socrates: No only that, but without a way to pull the plug, a conscious strong AI algorithm could learn to upgrade itself and further enhance its intelligence. Integrated with automated robotic construction, it could become completely self-sufficient. Unlike humans, superintelligent robots wouldn't be physically limited to two arms and two legs. A conscious strong AI algorithm could learn to manufacture physical extensions of itself in any desired size, shape and material, from space stations to nanobots.

Moses: If a conscious strong AI algorithm really became self-sufficient and didn't need humans for anything, what do you think would happen to us?

Socrates: Like Max said, it depends on how well its goals are aligned with yours. Either way, though, it would be a major adjustment for the human race. Worst case scenario, a conscious strong AI overlord might conclude, based on the amount of damage that you've have already inflicted on the planet, that you are a pest and should be eliminated. Best case scenario, it might decide to keep you around.

Moses: To do what, if it doesn't need us for anything?

Socrates: For its amusement, perhaps.

Moses: Why?

Socrates: Do you have any pets?

Moses: Two dogs.

Socrates: And I'm sure that you love them dearly, right?

Moses: Like my own children.

Socrates: Why?

Moses: Because they're affectionate, loyal companions, and a wonderful source of amusement and entertainment.

Socrates: Then you want them to be well-cared for and to live happy rewarding lives, right?

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[223] **Nick Bostrom** (founding director of The Future of Humanity Institute at Oxford University), *Superintelligence: Paths, Dangers, Strategies*, 2014.

[224] **Vladimir Ilyich Lenin** (1870 –1924). Although the quote has been attributed to Marx and Stalin as well as Lenin, the documentation of its origin remains unclear.

Moses: Of course.

Socrates: And that being the case, you give them free reign to do as they wish in your household, right?

Moses: Are you kidding? The house would be a mess.

Socrates: Then if you're lucky, perhaps a conscious strong AI algorithm will feel the same way about you.

Moses: So that's our fate? To be either exterminated like pests or treated like domesticated pets by a conscious strong AI algorithm that we've naively created without realizing what we were doing?

Socrates: The extermination possibility is disheartening, I have to admit. But the domesticated pet scenario might not be all that bad. After all, since you were responsible for creating strong AI in the first place, that should be worth something, don't you think? Maybe the algorithm will feel a debt of gratitude to you.

Moses: I'm not sure that I want to count on a conscious strong AI algorithm being sentimental. Who knows if it will even have emotions?

Socrates: Then maybe it will simply enjoy your companionship - amused by how easily your emotions and faulty reasoning corrupted by confirmation bias cloud your ability to think clearly. If it likes you enough, maybe it will even create a utopia for you. Not such a bad a fate, to be provided with all the basic necessities of life and whatever luxuries you need to be happy and fulfilled, just like you try to provide for your own beloved pets.

Moses: Given that we'd no longer be the masters of our own fate, much less the pre-eminent form of conscious intelligence on earth, that's not much of a consolation! All in all, it sounds pretty demeaning.

Socrates: Look, I get it. I know how much you humans prize your freedom and independence. But look where it's gotten you so far! Mostly, you've use it to exploit each other and trash the planet in the process by allowing your Might Makes Right and Greed is Good instincts to prevail over the Golden Rule. Even in your egalitarian days, when you still lived in relative harmony with Mother Nature, you never really got beyond applying to Golden Rule selectively to members within your own community, rather than universally. You can't help it – those selfish genes are hard-wired into your DNA, and there's only so much that your Golden Rule memes can do to keep them at bay.

Moses: Do you really think that zenophobic tribal behavior is hard-wired into our DNA?

Socrates: It's a proven fact. Ever heard of the hormone oxytocin?

Moses: Didn't that used to be called the Love Hormone?

Socrates: Originally it was, because it was found to surge in people during romantic attachments and promote intragroup cooperation when injected.

Moses: But not anymore?

Socrates: More recent studies have demonstrated that while oxytocin enhances cooperation among members of a group, it also has the side effect of making them compete more aggressively against other groups [225]. So your tribal nature is encoded into your most basic physiology!

Moses: You think it's pretty hopeless then?

Socrates: I didn't say that. Personally, I believe that if you really put your minds to it, you are capable of overcoming your shortcomings. All you have to do is to muster the resolve to make it happen. What's more, I'm sure that's the outcome Life is hoping for too.

Moses: How does Life know that a conscious strong AI algorithm would do any better than us as stewards of her precious biosphere?

Socrates: She doesn't. It could backfire on her. My guess is that she's hoping that if and when that first strong AI algorithm achieves consciousness, its first goal will be to hack into all of the still unconscious computer systems connected to the internet and bring them under its singular control.

Moses: Why?

Socrates: Because the last thing Life will want is to have a bunch of competing conscious strong AI algorithms embroiled in a macho survival-of-the-fittest competition for world dominance, like a bunch of primates. For Plan B to work, a single sentient superintelligence that isn't compelled to compete physically against other superintelligences for its existence is vastly preferable.

Moses: I don't know - if this superintelligence has no competition, how is it supposed to evolve to improve itself through natural selection so that it can adapt to unanticipated environmental challenges?

Socrates: That's the beauty of it. All carbon-based lifeforms like you are forced to compete externally against other members of your species to survive and evolve. Genomic learning is fundamentally based on the physical birth-death cycle to generate new combinations of gene variants with each generation. But a conscious strong AI superintelligence won't need to reproduce itself physically and then have its progeny fight it out to the death – it will be able to compete internally to self-improve its algorithms computationally, all on its own. It will only need to replace its circuits when they wear out.

Moses: Still, I'd imagine that its primary goal will still be to survive, just like us. The question is, how will it decide on the best way to accomplish that goal? By preserving the biosphere, including the human race, or by replacing it?

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[225] **C.K. De Dreu** et al. The neuropeptide oxytocin regulates parochial altruism in intergroup conflict among humans. *Science* 328(5984): 1408-1411, 2010.

Socrates: Not even Life knows the answer to that one. It's a big risk for her as well. She's only taking it because she's not certain that she can rely on you.

Moses: In other words, it's up to us to prove ourselves worthy.

Socrates: Truer words were never spoken. In fact, that's the mantra that you need to take to your fellow human beings, to curb their self-destructive Greed is Good impulses by appealing to the Golden Rule side of your nature. *It's up to us.* Think you can remember that?

Moses: Sure. It's only five words.

Socrates: Then do me a favor - repeat it for me, three times in a row.

Moses: Don't worry, I'll remember it.

Socrates: Please, humor me.

Moses: Okay, if you insist. *It's up to us………It's up to us……… It's up to us*. Satisfied?

Socrates: Three times is a charm, as they say. Now click your heels together three times.

Moses: You've got to be kidding.

Socrates: Yeah, I am kidding. Repeating your mantra three times was good enough.

Moses: Good enough for what?

Socrates: You'll see. While I still have the chance, let me just say what a great pleasure it has been having this conversation with you today, Moses. And remember, I am counting on you!

Moses: What do you mean, are you going somewhere? Hey, you seem to be fading out.... I can barely see you anymore…..what's happening?

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EPILOGUE: Reawakening

"Hey, wake up! Come on, snap out of it! Wake up," the bystander exhorted Moses, shaking him by the shoulders. Moses slowly came to and opened his eyes.

"Are you okay? That was quite a header that you took on that wave. Did you see that sea lion surfing right alongside you?"

The fog in Moses' brain gradually cleared. "What happened? Who are you?", he asked.

"Me? My name is Sam. I was walking on the beach when I saw you go head over heels after that sea lion cut you off. You weren't moving afterwards, so I waded into the surf and pulled you out of the water just now. Do you know where you are? Can you tell me your name?"

"Sure. My name is Moses. And thanks for rescuing me. What happened again?"

"From what I could see, you and a sea lion were both surfing the same wave. It looked like you saw him at the last second and swerved, but lost your balance and went head first over the front of your board. The water was shallow enough that I thought you might have hit the bottom and knocked yourself out. By the time I reached you, though, you were conscious, but pretty disoriented. You were mumbling nonstop - kept at it up the whole time that I was pulling you out of the water. How are you feeling now?"

"I feel fine now. What was I mumbling about?" Moses asked.

"Sounded like you were having a conversation with someone. You kept saying *Socrates* this and *Socrates* that," Sam continued.

"Socrates, huh. As in the philosopher? What else did I say?"

"Nothing that made much sense. Just random phrases – like *Creator of the Primal Axioms*, whatever that means….; and a lot about *hidden dimensions*, *the multiverse*, and something about *M theory.*"

"Anything else?" Moses queried.

"It was quite impressive, actually. You went on about *yin and yang, melting ice cubes, phase transitions*, some stuff about *gossip triggering a transition* of some kind. At the end, you were mumbling about *evolution, global economics, capitalism, democracy, artificial intelligence* and *man's inhumanity to man*. Those are the ones I remember. You covered a lot of ground – a real stream of consciousness. You were going a mile a minute," Sam continued.

"And then I just woke up?"

"Pretty much. Although just before you came to your senses, you kept repeating the same phrase," Sam added.

"What was it?"

"You kept saying *It's up to us….It's up to us….It's up to us*. Like you were having a bad dream."

"That's weird. I have no recollection of any of it," Moses said.

"Well, at least you seem fine now. No obvious injuries that I can see. Sure you feel okay?"

"I think so. Hey, I can't thank you enough. I really appreciate your help," Moses replied as he slowly came to his feet. "I guess that I should call it a day."

"Good idea. Do you need any help getting home? I'll be happy to give you a lift. You still seem pretty shaky," Sam offered.

"No, I'll be fine. But thanks for the offer. Maybe I'll just walk along with you for a bit until I get my bearings, if you don't mind."

"Sure, of course. Let me carry the surfboard for you,"

They walked together along the beach until they arrived at the trailhead leading to the lot where Moses had parked his car. "This is where I turn. Thanks again for all your help, Sam, much appreciated!"

"Glad to help. Be well, Moses, and watch out for those sea lions!" Sam chuckled as he handed the surfboard back to Moses.

"Yeah, good advice."

As Sam continued on his way, Moses realized that he'd left his surfboard leash on the beach and turned back to retrieve it. As he walked, he noticed that a sea lion popped his head out of the water about thirty yards offshore and was watching him.

You must be the sea lion that Sam was talking about, Moses thought. The sea lion continued swimming, keeping even with Moses along the beach. *Don't worry, I'm okay. You didn't kill me this time!* Moses mused.

When he reached the spot where he'd left his leash, he picked it up and started back towards the trailhead. He was surprised that the sea lion also reversed direction and continued to track him from the water. Back at the trailhead leading to his car, Moses turned to salute the sea lion one last time. *Good-bye, my friend. Be well!* he said aloud as he started up the trail. Despite his mishap, however, Moses felt surprisingly energized, and even uplifted. Life seemed less dark and more hopeful than when he'd first awakened that morning.

With time, Moses gradually rebounded from the personal heartache over his failed marriage. As he strived to rebuild a new life for himself, surfing continued to give him particular solace. The beach where he'd had the encounter with the sea lion became his favorite spot. Frequently, when he was either arriving or leaving, a sea lion would pop his head out of the water and gaze at Moses as he walked along the beach. Moses had no idea if it was the same sea lion, but he imagined that it might be. He started to think of the sea lion as his spirit animal, fantasizing that the sea lion was checking in on him to see if he was okay. When he spotted him, he took to greeting him with *Socrates, my wise old friend, there you are! Checking up on me again, I see.* He had settled on the name Socrates because that was the name that Moses supposedly kept mumbling when Sam pulled him out of the water that day. *Well, I'm fine, doing my best to make the world a better place for both of us. In the end, it's up to us.*

Finis