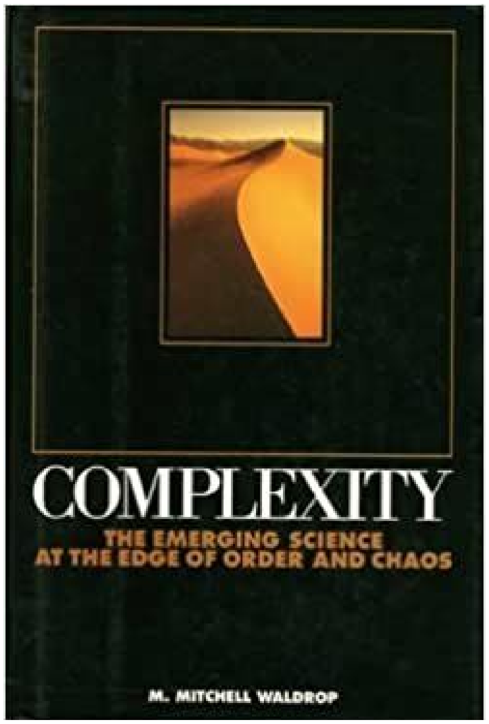
"An adaptive agent is constantly playing a game with its environment. What exactly does that mean? Distilled to the essence, what actually has to happen for game-playing agents to survive and prosper? Two things: prediction and feedback." —*John Holland*



Summary: *Complexity* is about the rise of the legendary Santa Fe Institute and their revolt against linear, reductionist thinking.

For the uninitiated, the Santa Fe Institute is a theoretical research institute founded in an old convent chapel in New Mexico. The year was 1984, and multiple Nobel Laureates were involved.

In this abandoned church, wildly different disciplines collided: economists, physicists, computer scientists, bomb makers and biologists—who formed an appreciation that most problems in life are multivariate and nonlinear.

The best part about this book? Author M. Mitchell Waldrop warmly welcomes the reader into the ensuing intellectual dialogue. *It feels like you're there:* sparing with Murray Gell-Mann, Kenneth Arrow, Brian Arthur, Stuart Kauffman, John Holland, Chris Langton, and George Cowan—trying to figure out the mysteries of life.

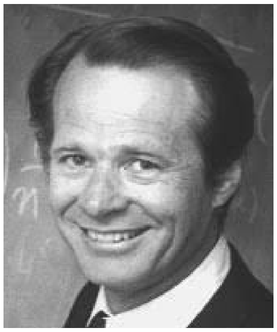
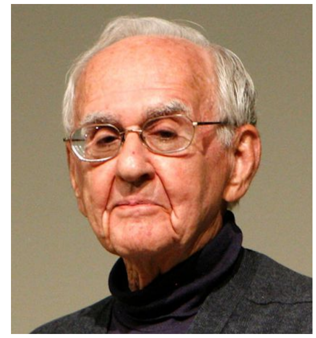
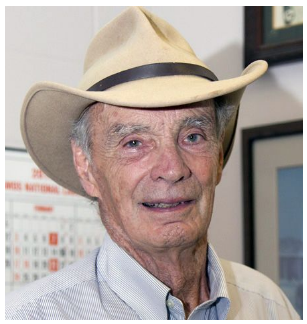
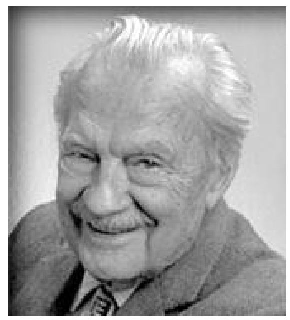
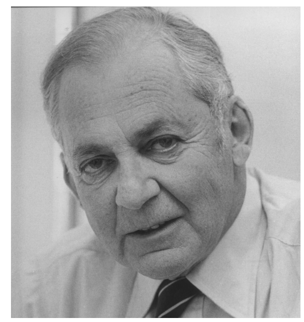
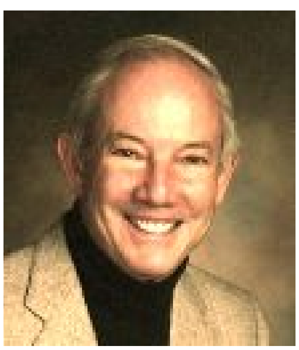
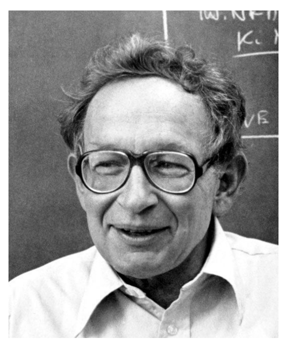
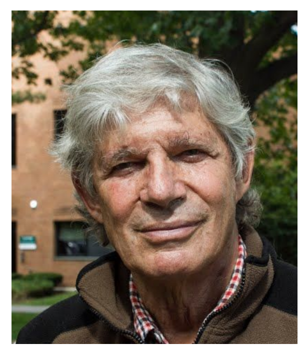
Buckle up for some intellectual horsepower, and get ready to embrace a new science of interconnectedness, coevolution, structure, and chaos—or what *The Washington Post* called "*The most exciting intellectual adventure story of the year."*

"The word "emergence" seemed to crop up frequently. And most of all, there was this incredible energy and camaraderie in the air—a sense of barriers crumbling, a sense of new ideas let loose, a sense of spontaneous, unpredictable, open-ended freedom. In an odd, intellectual sort of way, the workshop felt like a throwback, like something right out of the Vietnam-era counterculture. And, of course, in an odd, intellectual sort of way, it was."

M. Mitchell Waldrop

Author bio: M. Mitchell Waldrop earned a Ph.D. in elementary particle physics at the University of Wisconsin in 1975, and a Master's in journalism at Wisconsin in 1977. From 1977 to 1980 he was a writer and West Coast bureau chief for Chemical and Engineering News. From 1980 to 1991 he served as a senior writer at Science magazine, where he covered physics, space, astronomy, computer science, artificial intelligence, molecular biology, psychology, and neuroscience. In addition to "Complexity," he is the author of "Man-Made Minds" (1987). His new book about the history of computing, "The Dream Machine," will be published by Viking Penguin in August 2001. In his spare time he is an avid cyclist and swimmer. He lives in Washington, D.C. with his wife, Amy E. Friedlander, and their dog, Betsy.

Meet some of the brainiacs

 Dick Slansky physicist	 Peter A. Carruthers physicist	 Murray Gell-Mann* physicist	 George Cowan nuclear scientist
 David Pines physicist	 Stirling Colgate physicist	 Nicholas Metropolis physicist	 Herb Anderson nuclear physicist
 W. Brian Arthur economist	 Kenneth Arrow* economist	 Philip Anderson* physicist	 Stuart Kauffman biologist

* Nobel Prize Laureates

The Santa Fe Institute (SFI) was founded in 1984 by the first eight gentlemen you see above. Of these founding eight scientists, six had worked at Los Alamos National Laboratory thirty-seven miles to the northwest in Santa Fe.

What did they seek to accomplish? An exploration of complex systems by way of cross-discipline fusion. Complex systems—like a human cell, the economy, or our solar system—are unique in that they have distinct properties such as nonlinearity, emergence, adaptation, feedback loops, and spontaneous order (and more!).

The **Santa Fe Institute** was created to be a *visiting* institution, with no permanent or tenured positions, a small group of resident faculty and postdoc researchers, a large visitors program, and a larger group of *external* faculty.

The motivation of this structure was to encourage active turnover in ideas and people—shuffling the deck, so to speak—allowing the research to remain on the cutting edge of interdisciplinary science. Today, the Santa Fe Institute continues to follow this organizational model.

Old Economic, New Economics

The book begins by introducing us to Brian Arthur, the brilliant, doughty Irishman. In 1979, Arthur has a revelation: **the economic world is fluid, ever-changing, and alive,** and he begins constructing a new vision for economics:

Old Economics	**New Economics**
• Decreasing returns	• Much use of <u>increasing returns</u>
• Based on 19th-century physics (equilibrium, stability, deterministic dynamics)	• Based on biology (structure, pattern, self-organization, life cycle)
• People identical	• Focus on individual life; people separate and different
• If only there were no externalities and all had equal abilities, we'd reach Nirvana	• Externalities and differences become driving force. No Nirvana. System constantly unfolding.
• Elements are quantities and prices	• Elements are patterns and possibilities
• No real dynamics in the sense that everything is at equilibrium	• Economy is constantly on the edge of time. It rushes forward, structures constantly coalescing, decaying, changing.
• Sees subject as structurally simple	• Sees subject as inherently complex
• Economics as soft physics	• Economics as high-complexity science

Arthur called his new economics "Increasing Returns," a name which fell far short of his excitement for it. In 1983, Arthur became one of the youngest endowed processors in Stanford's history at the age of 37. As he taught Population Studies and Economics, his increasing returns ideas were considered outrageous—even sacrilegious—in a time of Reagan and free market ideals, or what Arthur described as *"letting everybody be their own John Wayne and run around with guns."*

"But increasing returns cut to the heart of that myth. If small chance events could lock you in to any of several possible outcomes, then the outcome that's actually selected may not *be the best. And that means that maximum individual freedom—and the free market—might* not *produce the best of all possible worlds."*

Meet Kenneth Arrow

Turning point: While Arthur was strolling around Stanford's campus, Kenneth Arrow zipped up on a bicycle and asked him if he wanted to join "a meeting of economists and physicists at a small institute in New Mexico." He said yes. That's how all of this started: casual conversations, transfers of enthusiasm.

Kenneth Arrow: was an American economist, mathematician, writer, and political theorist. He was the joint winner of the Nobel Memorial Prize in Economic Sciences with John Hicks in 1972.

In economics, he was a major figure in post-World War II neo-classical economic theory. Many of his former graduate students have gone on to win the Nobel Memorial Prize themselves. His most significant works are his contributions to social choice theory, notably "Arrow's impossibility theorem", and his work on general equilibrium analysis. He has also provided foundational work in many other areas of economics, including endogenous growth theory and the economics of information.

Come Together

One of the gripes these scientists had was the departmentalism of science—the fragmentation process created in scientific institutes and universities. *"The traditional disciplines had become so entrenched and so isolated from one another that they seemed to be strangling themselves."* The Santa Fe Institute would embody the opposite: fusion and collaboration, no matter your scientific creed.

Just as Schrödinger, a physicist, whose book *What is Life?* had cross-pollinated with biology and even inspired Watson & Crick, the SFI team invited diverse disciplines to their retreat. Though I imagine a mostly-physicist group may have their penchants: *"Almost by definition,"* says Cowan, *"the physical sciences are fields characterized by conceptual elegance and analytical simplicity. So you make a virtue of that and avoid the other stuff."*

Computers and nonlinear dynamics

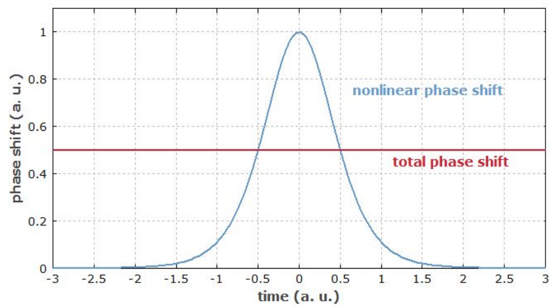
Recall at this time, personal computers were booming, further empowering scientific and mathematical pursuit with their computing power.

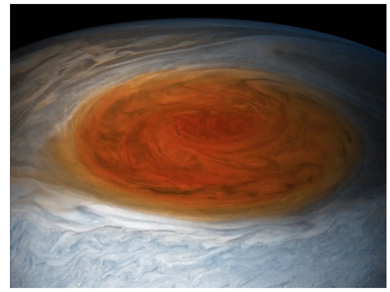
Computer simulations were being called a "third form of science" standing halfway between theory and experiment.

Physicists could work with computer programmers to model messy, complex systems which increased the vigor around **nonlinear dynamics.**

Can the sum be greater than the parts? Indeed.

Sound is a linear system. Light is a linear system. But a lot of things—the human brain, the economy—are nonlinear. Computers could crunch these systems, which catalyzed a step-function of new knowledge, e.g. what does a canal wave pulse have to do with quantum field theory and Jupiter's red spot? Solitons.





"Except for the very simplest physical systems, virtually everything and everybody in the world is caught up in a vast, nonlinear weeb of incentives and constraints and connections."

Phil Anderson and collaboration

Creating an interdisciplinary institute is hard. Just ask Phil Anderson, a Nobel Laureate. *"The academic landscape is littered with the corpses of fancy new institutes that failed miserably; if they didn't get taken over by crackpots, they generally just sank into high-minded stagnation."* Example: Institute for Advanced Study in Princeton. Good at math, bad at collaborating. But they were able to entice Anderson with their zeal to "reverse the tide of reductionism," which was very much in-line with his intellectual desires.

"To Anderson, emergence in all its infinite variety was the most compelling mystery in science."

A lot of the early momentum for the Santa Fe Institute was created by hosting workshops.

> *"In particular, the founding workshops made it clear that every topic of interest had at its heart a system composed of many, many "agents." These agents might be molecules or neurons or species or consumers or even corporations. But whatever their nature, the agents were constantly organizing and reorganizing themselves into larger structures through the clash of mutual accommodation and mutual rivalry. Thus, molecules would form cells, neurons would form brains, species would form ecosystems, consumers and corporations would form economies, and so on. At each new level, new emergent structures would form and engage in new emergent behaviors.* ***Complexity, in other words, was really a science of emergence."***

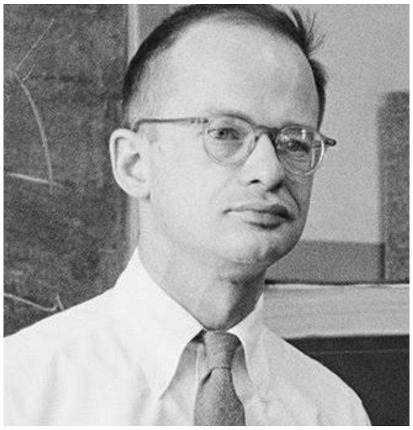
Secrets of the Old One*

**Albert Einstein's favorite metaphor for the creator of the universe was the "Old One."*

In this splendid chapter we meet the ferociously intelligent **Stuart Kaufmann**, a biologist invited to the Santa Fe Institute. If you want to get a sense of the intellectual horsepower we're dealing with, check out this video interview with Kauffman. Favorite quote: *"Without any selection doing so, the biosphere is creating its own future possibilities of becoming. That's not in Darwin. That's emergence."*

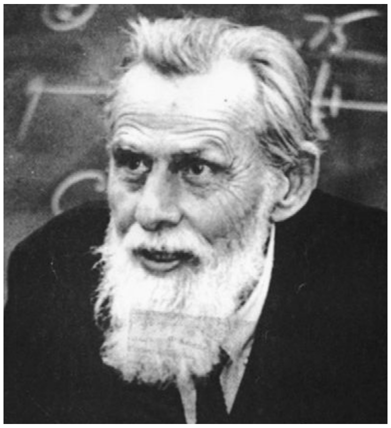
The concept of the **adjacent possible** is both practical and valuable. It can be applied to almost all fields from biology to venture capital.

In 1966, a full 18 years prior to the Santa Fe Institute's creation, Kauffman brazenly emailed Warren McCulloch of MIT—one of the grand elders of neurophysiology and artificial intelligence—to share his work on genetics networks using lightbulbs to model their behavior (observing that living cells scale at approximately the square root of the number of genes it had). McCulloch, a devout Quaker, invites Kauffman and his wife to drive across the country and stay with his family in Cambridge. McCulloch would connect Kauffman to people and resources he never dreamed of, and this is a great example of how a single relationship can completely transform your life.



Walter Pitts

McCulloch (right) worked closely with Walter Pitts (left) who, at the age of 18, had co-published a paper entitled *"A Logical Calculus of the Ideas Immanent in Nervous Activity"* in which they claim the **brain could be modeled as a network of logical operations such as *and, or, not* and so forth.** This idea was both revolutionary and immensely influential at the time. It is the first example of what would now be called a neural network, and also the first attempt to understand **mental activity as information processing**. AI and cognitive psychology were never the same.



Warren McCulloch

"And it was clear that genetic networks and neural networks were fundamentally the same thing."
—Stuart Kauffman

In his friendly mentoring way, McCulloch introduced Kauffman to Marvin Minsky (who would go on to win the Turing award in 1969), the resident guru of MIT's artificial intelligence group, who gave him access to MIT's powerhouse computers to run simulations of thousands of genes interacting.

> *"The dynamics of his genetic regulatory networks turned out to be a special case of what the physicists were calling nonlinear dynamics. . . mathematically, their behavior was equivalent to the way all the rain falling on the hillsides around a valley will flow into a lake at the bottom of the valley. In the space of all possible network behaviors, the stable cycles were like basins—or as the physicists put it, "attractors."*

How did life start?

Kaufmann and company ponder how life began, favoring autocatalytic molecules: *"Ultimately, in fact, you could imagine the winnowing process* [of natural selection] *giving rise to DNA and all the rest. The real key was to get an entity that could survive and reproduce; after that, evolution could do its work in comparatively short order.*

The Berkeley Nobelist Melvin Calvin had explored several autocatalytic scenarios for the origin of life in his 1969 book, *Chemical Evolution.* Otto Roessler and Manfred Eigen we're also in hot pursuit. Ideas were evolving.

Horsetail Falls, Sierras

Stuart Kauffman has a near religious moment at one of his favorite hiking spots: Horsetail Falls, near Lake Tahoe.

His years of studying, theorizing and simulating had paid off: one of his simulations had shown that **autocatalytic sets did form under conditions**—conditions he had predicted from his theorems about abstract networks. Life can emerge.

“And suddenly I knew that God had revealed to me a part of how his universe works. It was a lovely moment, the closest I’ve ever come to a religious experience.”

Arthur and Kauffman would kick things off at the first Santa Fe workshop.

Showtime

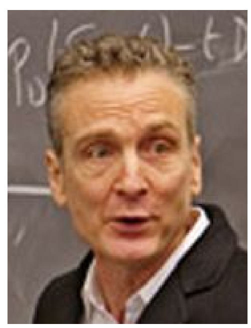
To center his mind, our doughty Irishman, Brian Arthur, practices tai chi to calm the nerves. He then kicks off the 10-day Santa Fe workshop with his topic of increasing returns, a dynamic in which economic winners compound their lead, while losers fall further behind—all of which creates instability, not “equilibrium.” **Think: Amazon.**

Kauffman would also give a talk, illuminating the audience by describing our economy as an autocatalytic system.

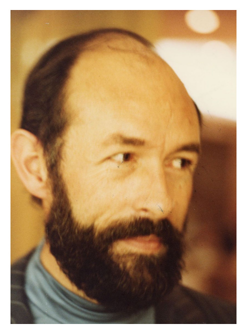
Who else attended this first Santa Fe Institute workshop? The who’s who of academia:

Hollis Chenery
head of research at World Bank; owns Secretariat

Larry Summers*
Harvard whiz-kid, chief economist at World Bank



José Scheinkman
pioneer in chaos theory applied to economics



David Ruelle
Co-founder of chaos theory; Belgian physicist

**had to use this picture*

The economists’ ambitious thinking invited skepticism from the (many) physicists in attendance. To say it was a polarized crowd is an understatement, and it took some time to find common ground.

> *“In their own minds, physicists are the aristocracy of science. From the day they sign up for Physics 101, they absorb the culture in a thousand subtle and not-to-subtle ways: they are the heirs of Newton, Maxwell, Einstein, and Bohr. Physics is the hardest, purest, toughest science there is. And physicists have the hardest, purest, toughest minds around.*

John H. Holland spoke second after Brian Arthur on the topic of **complex, adaptive systems** by defining their characteristics:

1. Lots of "agents" whose environment is produced by its interactions with the other agents in the system
2. Constantly changing, i.e. nothing is fixed
3. Highly dispersed, i.e. no master planner
4. Coherence as a function of competition and cooperation between agents
5. Many levels of organization, i.e. proteins/lipids/nucleic acids → cells → tissue → organ → organism → ecosystem, etc.
6. Constantly revising and rearranging their building blocks as they gain experience
7. Anticipating the future
8. Many niches, or areas of expertise
9. Equilibrium doesn't equal stability. . . equilibrium equals death (system ceases to evolve)
10. Perpetual novelty

Holland's talk was so well-received and influential, that the organizers changed the workshop's theme from complex systems to **complex, *adaptive* systems.**

"So there you have the economic problem in a nutshell: How do we make a science out of imperfectly smart agents exploring their way into an essentially infinites space of possibilities?" —Arthur to Holland


John Holland

What captivated Holland as early as high school before MIT wasn't that science allowed you to reduce everything in the universe to a few simple laws. It was just the opposite: that science showed you how a few simple laws could produce the enormously rich behavior of the world. . .

"It really delights me. Science and math are the ultimate in reduction in one sense. But if you turn them on their heads, and look at the synthetic aspects, the possibilities for surprise are just unending. It's a way of making the universe comprehensible at one end and forever incomprehensible at the other end."

"So once again," says Holland, "you have a system exploring its way into an immense space of possibilities, with no realistic hope of ever finding the single "best" place to be. All evolution can do is look for improvements, not perfection."

Holland published *Adaptation in Natural and Artificial Systems* in 1975. It laid out the genetic algorithm in exquisite details. It was greeted with "resounding silence" but kept some traction with the AI community. He goes back to first principles and starts thinking about adaptive systems as playing a game with its environment. What is required to survive and prosper? **Two things: 1) prediction, 2) feedback.**

He then layered in Hebbian reinforcement by which if the agent gets a positive response from the environment, the classifier response should be strengthened. He was early, but eventually proven right. Holland became immensely famous for his work, and his ideas were propagated by over forty Ph.D. students he'd advised.

Chris Langton is an American computer scientist and one of the founders of artificial life. As a young adult he suffered a horrendous hang-gliding accident near Grandfather Mountain in North Carolina that probably should have killed him. It took 14 operations to put him back together, and he emerged resilient.

He was a big contributor at the Santa Fe Institute given his experience programming AI simulations like the Game of Life and his conclusive findings that self-reproduction once considered to be an exclusive characteristic of living things, could indeed be achieved by machines.

Chris Langton
Santa Fe Institute in 1989

Okay, lots of smart people but what did they do?

By page 240 I was thoroughly enthralled by all the intellectual horsepower and academic elite at SFI, but a nagging question kept nagging my subconscious: *What did this amazing group actually produce?* I attempted to organize the answer into quadrants to describe what this diverse group studied, how they studied it, and the ultimate output:

Systems studied: ● history of languages ● evolutionary computation ● dynamics of financial markets ● metabolic and ecological scaling laws ● structure and dynamics of species interactions including food webs ● evolutionary diversification of viral strains ● interactions of primate social groups ● emergence of hierarchy and cooperation in the human species ● fundamental properties of cities	**Methods of studying:** ● agent-based modeling ● network theory ● computational immunology ● physics of financial markets ● genetic algorithms ● physics of computation ● stochastic learning ● machine learning
Tools from other disciplines: ● information theory ● combinatorics ● computational complexity theory ● condensed matter physics ● phase transitions in NP-hard problems	**Foundational contributions to:** ● artificial life modeling real organisms and ecosystems ● chaos theory ● genetic algorithms ● complexity economics school of thought ● complex networks and systems biology ● "Evolution of Human Languages" project (Proto-Human language) ● econophysics

The Santa Fe Approach

The end of this book gets really good by combining all the seemingly isolated brilliance across disciplines into larger, overarching constructs with which to better understand life (and thrive). One seminal construct is known as the Santa Fe approach:

Instead of emphasizing decreasing returns, static equilibrium, and perfect rationality of the neoclassical view, they would emphasize increasing returns, bounded rationality, and the dynamics of evolution and learning.

Instead of basing their theory that were mathematically convenient, they would try to make models that were psychologically realistic.

Instead of viewing the economy as some kind of Newtonian machine, they would see it as something organic, adaptive, surprising, and alive.

Instead of talking about the world as if it were a static thing buried deep in the frozen regime, they would learn to think about the world as a dynamic, ever-changing system poised at the edge of chaos.

Instead of operating deductively, they would favor inductive mode.

Let's also acknowledge that Austrian economist Joseph Schumpeter was trumpeting a lot of these ideas in 1924.

One of my favorite parts of the book is when John H. Holland talks about meteorology as a perfect metaphor—and example—of the systems they were trying to understand:

> *"Look at meteorology. The weather never settles down. It never repeats itself exactly. It's essentially unpredictable more than a week or so in advance. And yet we can comprehend and explain almost everything that we see up there. We can identify important features such as weather fronts, jet streams, and high pressure systems. We can understand their dynamics. . . how they interact to produce weather on a local and regional scale. In short, we have a real science of weather—without full prediction. And we can do it because prediction isn't the essence of science. The essence is comprehension and explanation.*

Reference: In his 1984 book, *The Evolution of Cooperation*, Robert Axelrod pointed out that the TIT FOR TAT strategy used in game theory can lead to cooperation in a wide variety of social settings, i.e. "live-and-let-live" in World War I. TIT FOR TAT's success had profound implications for biological evolution and human affairs.

Reference: we learn of Nicolas Léonard Sadi Carnot, the "father of thermodynamics" who, at the tender age of 27, published his sole paper in 1824: *Reflections on the Motive Power of Fire*. He died of cholera at the age of 36.

"Humanity is gravely threatened by superstition and myth, the stubborn refusal to recognize the urgent planetary problems, and generalized tribalism in all its forms."