Systems Science, Cybernetics, and Complexity

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Abstract

Systems science, cybernetics, and complexity all evolved out of concerns for understanding complex phenomena in science. They also share many of the same theoretical roots, as well as histories which converge across leading figures and places in time. They can be conceived as three realms which shared and competed for prominence. All have influenced and been incorporated into scientific disciplines, though much of the history has been forgotten by current generations.

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Those historical roots remain relevant and important to future progress in science. This chapter provides a brief summary of the history and foundations of these domains.

Keywords

Systems science · Cybernetics · Complexity · Systems biology · Modeling relation · Evolution of science

Introduction

At the heart of science is a search for order. Science is grounded in the belief that the universe is neither arbitrary nor capricious, but follows patterns that can be discovered and understood.

The roots of Western science lay in ancient Greece. Like earlier civilizations, they had developed a complex and well-ordered cosmology built around deities who embodied what they believed to represent the essential foundations of order in the world: light and dark, love and hate, male and female, and so on. This belief system was captured most eloquently in the tales of Homer, the Iliad, and the Odyssey. It explained the struggles that humans faced as they journeyed through a world governed by forces far out of their control.

During the same period, Thales of Miletus, born in the seventh century B.C., set the stage for an objective, rational science, devoid of mysticism. The goal was to understand the universe using only observation and reasoning. "Nature was to be explained in terms of nature itself, not of something fundamentally beyond nature, and in impersonal terms rather than by means of personal gods and goddesses" (Tarnas 1991, p. 20).

It is important to remember that the ancient Greeks, and other early scientists, had no telescopes or sophisticated instruments for measuring celestial movements. They could only observe and conjecture.

It is hard to imagine the experience of gazing into a clear night sky, centuries ago. Without haze and emissions, and without ambient light from cities, most humans must have seen a view much like that in the remotest deserts today. It is easy to understand how – for those who had time to pay attention – there would have been a sense of awe about the order that existed. Contrast that with the unpredictability of the time about weather and storms, disease and famine, and all manner of natural events on Earth. It is no wonder that such images set the stage for modern science; chaos and order, Eros and Logos.

Despite our advances, questions about order and chaos continue today. Different cosmologies offer different explanations. In one, the Big Bang created a universe in which entropy was the ultimate force. The universe moves from a state of high energy to low, like a clock winding down, eventually ending in "heat death." By itself, this did not explain an increasingly expanding universe, nor increasing novelty and complexity. Other cosmologies have suggested that order, and even intelligence, exists in the very fabric of the universe itself. Still others see the universe as a place of ongoing emergence, as the universe continues to evolve, exhibiting new and unpredictable forms of order.

The Greeks faced similar questions, in different forms, 2800 years ago. As summarized by Tarnas (1991):

> From Thales on, each philosopher had proposed his particular theory as to what was the true nature of the world, with each theory contradicting the others, and with a growing tendency to reject the reality of more and more of the phenomenal world revealed by the senses. The result was a chaos of conflicting ideas, with no basis upon which to certify one above the rest. Moreover, the natural philosophers seemed to have been constructing their theories about the external world without adequately taking into account the human observer, the subjective element. By contrast, the Sophists recognized that each person had his own experience, and therefore his own reality. In the end, they argued, all understanding is subjective opinion. Genuine objectivity is impossible. All a person can legitimately claim to know is probabilities, not absolute truth (p. 27)

The resolution was an attempt at simplicity. Search for the most essential properties which could explain all others.

For the Greeks, math was an early candidate for order. Pythagoras (or one of his followers) is credited with stating something like, "all is number." Galileo is frequently quoted as saying, "Mathematics is the language in which God has written the universe." Recent scientists continue to make similar claims, such as "mathematics is the language of the universe."

While ancient Greeks did not invent math, the Pythagoreans developed it into its own system of order. Characteristics embodied by the deities could represent what was constant, but so could numbers. This fed into the cosmology developed by Plato, in which "Ideas," or "ideal forms," were the essence of order.

Plato's understanding of Idea was built around the distinctions between *being* and *becoming*. "All phenomena are in a never-ending process of transformation from one thing into another..." (Tarnas 1991, p. 9). *Becoming* could be observed, but was then subject to human interpretation and misunderstanding. *Being* was an immutable state. It could be apprehended through discovering the mathematical order which defined the phenomenon in question.

These concepts are also captured in Plato's notion of ideal forms. An actual entity is only an imperfect representation of its underlying ideal. Beauty, for instance, represented an ideal, as embodied in the Greek goddess Venus. The most beautiful women closely conformed to the ideal, without fully embodying it. Forms were considered to be immortal, similar to the deities. But also like deities, Plato's ideal forms could not be touched or tested. They could only be discovered through mathematics, which could unlock the intricate order of the universe.

Plato, like the Pythagoreans, maintained a sense of the mystical or spiritual.

> For at the heart of Plato's conception of the world was the notion of a transcendent intelligence that rules and orders all things: divine Reason is "the king of heaven and earth." The universe is ultimately ruled not by chance, materialistic mechanics, or blind necessity, but rather by "a wondrous regulating intelligence" (Tarnas 1991, p. 44).

The search for ultimate order, inherited from our Greek ancestors, continues today. This chapter provides a brief summary of some of the attempts to describe order as it has evolved in the complex biosphere of Earth.

Systems science, cybernetics, and complexity science each offered their own modes of explanation for order, though with many commonalities in their underlying interests and intentions. As noted by François (1999), these roots also trace back to the Greeks, who had words for systems (*sustema*) and cybernetics (*kubernetes*, used by Plato to mean "helmsman" or "pilot") already in use.

Systems science, in its current form, was founded primarily in theoretical biology, based on the work of individuals such as Rashevsky, Bertalanffy, Rosen, and others. It was, in part, a rejection of the idea that all science was physics (e.g., that properties of particle physics could explain life.) In its own way, it was a search for large, if not universal, patterns of order, which might exist beyond material properties. For instance, could there be forms of life beyond Earth which followed similar principles of organization, but were not based on the same material necessities? It argued for the emergence of order in given contexts, an interdependent relationship between system and environment.

Cybernetics was birthed in neurological studies, attempting to understand information and communication. According to Umpleby et al. (2017), three key foci distinguish cybernetics models, a combination of regulation, self-organization, and reflexivity. Early cybernetic work is often associated with the development of computers and robotics. Later work took a constructionist view, creating second-order cybernetics. The mental constructs through which individuals interpreted the world were never absolute. They were relative to a given observer.

Much of the mathematical work which influenced early cybernetics also formed the foundations for computers. The model for neurons became binary switches, which were mathematically coded as 0's and 1's. Eventually, computers became models for brains. The search for order in complexity science began with such models, which were extrapolated to phenomena in the world.

Umpleby et al. (2017) have proposed that systems, cybernetics, and complexity, while sharing some commonalities, are distinct fields represented by their own associations, journals, and conferences. That view contrasts with the perspective of James Greer Miller, one of the founders of the Society for General Systems Research. In Miller's experience, "system" became a more commonly used term in the USA, where "cybernetics" was adopted in Europe, but referring to essentially the same principles. In a presentation to Miller's discussion group in 1951, Warren Weaver predicted that the second half of the twentieth century would be a time of the "science of complexity" [video minute 56:00]. Miller supported that view, saying he believed that General Living Systems Theory (his life's work) was, in fact, a part of this future complexity science.

As will be shown, the three domains of systems, cybernetics, and complexity shared more common history than is typically known. Understanding them in relation to each other may explain their collective importance.

Modern Science

There remain questions about what we can know, and how certain we can be of our knowledge. Strong tenants have developed, but they are seldom as absolute at they might appear. Science, for instance, is to be objective. It should not be a matter of conjecture or opinion, yet every choice of what to study, and how to study it, involves not only a prior perspective, but contains some elements of bias – if only in the choice of the subject itself. (Why study this, and not that?)

Science rejected the idea of "purpose" (i.e., teleology) as a guiding force. The universe came into being, it exists as it does, and there is no further reason needed. Existence is its own explanation. Within those boundaries, however, is there a reason for science? Or is there a reason for any human activity of any kind? If not, then at the least, science loses any foundation from which to speak to human issues of meaning or purpose, or of spirituality or morality, other than possibly as neurological phenomena occurring at particular levels of physiological development.

Science chose to rely on empirical testing done through measurement, with findings stated in mathematical terms. These practices certainly helped to sort out something of the "true nature of the world" as described by Tarnas (1991). Observation and measurement led to more accurate models of our solar system, long before humans traveled into space. Increasingly sophisticated tools such as the telescope and microscope allowed for direct human observation of both macroscopic and microscopic spaces. Accurate means of measurement helped to resolve disputes between competing theories (for instance, do heavier bodies of matter fall faster than lighter ones?)

Wigner (1960) explained the connections between mathematics and science. The interest of science is the discovery of regularities in nature. If there were no regularities, there would be nothing about which science could generalize. In physics, that interest extends to invariances, or laws of nature. It is due to the regularities of nature that discoveries have been made using mathematics, long before they could be subjected to empirical testing. (As noted by Wigner, Newton could only verify his theory of gravity to about 4% accuracy. It was later proven accurate to less than a ten-thousandth of one percent.)

Wigner was also clear, however, about the limitations. There are invariances which hold well enough in physics. In other realms of science, the regularities are less universal.

Every empirical law has the disquieting quality that one does not know its limitations. We have seen that there are regularities in the events in the world around us which can be formulated in terms of mathematical concepts with an uncanny accuracy. There are, on the other hand, aspects of the world concerning which we do not believe in the existence of any accurate regularities. We call these initial conditions (Wigner 1960, p. 7).

Accuracy, especially of predictions about future behavior, was always "within limits." Further, to read Wigner's (1960) description of mathematics is like revisiting Plato. He begins his treatise with a quotation from Bertrand Russell:

> Mathematics, rightly viewed, possesses not only truth, but supreme beauty – a beauty cold and austere, like that of sculpture, without appeal to any part of our weaker nature, without the gorgeous trappings of painting or music, yet sublimely pure, and capable of a stern perfection such as only the greatest art can show (p. 1).

The use of computers in science raised questions about the relationship to mathematics significantly. Computers have been able to run calculations, substituting for empirical experiments, that could never have been done by humans without them. The magnitudes of possible combinations, or the timeframes required to allow real-world experiments to occur, were simply out of reason. The power of computers became evident from their inception, through the work of Alan Turing and his colleagues in deciphering the encryption code of the German military in World War II. That power extended to targeting anti-aircraft guns with significantly increased accuracy and continued into the computer systems – and the Internet – that we now know.

The fastest supercomputer at present (currently at Oak Ridge National Laboratory in Tennessee) can process 200 quadrillion calculations per second (https://www.nytimes.com/2018/06/08/technology/supercomputer-china-us.html). Supercomputers have famously beat the best humans at games of chess and Go, and in Jeopardy (requiring natural language processing). There are advocates (even "prophets") of artificial intelligence such as Ray Kurzweil, who have predicted that computers will overtake human intelligence in the near future (https://www.youtube.com/watch?v=EyFYFjESkWU). Some are working towards digitizing human identities into an "augmented eternity" (see https://www.media.mit.edu/projects/augmented-eternity/overview/). Other leading figures, such as Elon Musk, founder of Tesla and SpaceX, have strong reservations about unregulated advancements in digital technologies (https://www.youtube.com/watch?v=6tBZA2rygcM&t=468s).

Every representation that humans create involves choices and limitations. William of Ockham argued for the greatest parsimony (the simplest explanation). The simplest and most general theories may be considered the most elegant. A critical question, however, is the importance of what was omitted.

Robert Rosen explained the relations between a theory or representation in science and the reality it attempted to capture, in terms of his *modeling relation*. The attributes of a phenomenon which are perceived to be of importance are captured in a formal model (typically using mathematics). Once the model is complete, it can be tested against the phenomenon to see how closely it fits. In science, this is the development and testing of hypotheses, which ideally continues on indefinitely as new knowledge is gained and the theory or model refined. In reality, the process is often less open or ideal.

The choices of attributes to be included in a model may be limited by many influences: the background and perspective of a researcher, the accepted theories of a given profession, the available technologies for observation or measurement at the time, etc. These kinds of limitations can be seen in the history that dates back to ancient Greece. Trusting only what could be directly observed and measured significantly increased confidence in the findings of an experiment. Concurrently, it eliminated phenomena in the world which could not be directly observed or measured as irrelevant or unimportant.

Obviously, that extreme description has changed over time, but vestiges have remained. Using physics and mathematics as the necessary foundations for science created a mechanistic view of the world which lasted for centuries (i.e., the Newtonian universe). It was "good enough" at the time, because no greater accuracy was required. It can still be seen, however, in the arguments made by the most extreme proponents of artificial intelligence. Neurons are tiny "machines" with certain processing speeds and power. Replicating that system is only, then, a matter of mapping the physical structure and the processing capacity of a human brain. From that must rise the human attributes that we witness.

It would be difficult to argue that science has not brought incredible progress to humankind, especially through applications in technologies. Many people's lives are easier, longer, and more advanced than most could have guessed even a century ago. Promises for the future overwhelm the imagination. At the same time, it would be easy to argue that humans have affected the only world we have, in ways that may be detrimental to our future existence. More importantly, we lack any current technologies for remedying the large-scale problems that we have created. Things that we did not see or measure may turn out to be of extreme importance.

The Search for Certainty

As noted, mathematics had become associated with science by the time of the Pythagoreans in ancient Greece. Euclid later perfected mathematics into geometry, as well as establishing a system of axioms by which propositions could be proven through logic (Einstein 1920). The universe took on a new level of order.

Euclidean geometry described a universe of two- and three-dimensional planes. Within that space, all of the measurements and relationships worked. Its truths remained intact for nearly two thousand years.

It was Copernicus who held to the Pythagorean dream of a simple universe, operating in mathematical harmony. He actually returned to writings from the ancient Greeks to find ideas of an Earth that moved, rather than remaining stationary as the center of the universe. Kepler "at last solved the ancient problem of the planets and fulfilled Plato's extraordinary prediction of single, uniform mathematically ordered orbits" (Tarnas 1991, p. 256).

With the creation of his telescope, Galileo was able to more closely observe the moon, planets, and stars. He not only confirmed the work of Copernicus and Kepler, but discovered features of the universe that had never before been guessed. And crucially, he reinforced the standards for measurement and objectivity in science. As described by Tarnas (1991):

> [Galileo] argued that to make accurate judgements concerning nature, scientists should consider only precisely measurable 'objective' qualities (size, shape, number, weight, motion) while merely perceptible qualities (color, sound, taste, touch, smell) should be ignored as subjective and ephemeral (p. 263).

It was not until 1637 A. D. that Descartes formally connected algebra with Euclidean geometry. Later that century, Newton formulated the laws of motion and universal gravitation and established the mathematical foundations for classical, or Newtonian, mechanics. In the process, he also invented calculus, the mathematics for describing change and motion. It was Newtonian mechanics which allowed for a vision of a perfectly ordered, mechanical universe, one which was governed entirely by the laws of motion. It was a universe which mimicked an immense clockwork of stars and planets and particles, all moving in perfect alignment with each other along mathematically predictable orbits.

Leibnitz proposed a principle of pre-established harmony between substances, such that any change affected all related substances. This established the grounds for a system of reciprocal constraints and set the stage for coherence in conceptual systems (François 1999).

Laplace took Newton's perfectly ordered universe from description to prediction. According to Mitchell (2009), "In 1814 he asserted that, given Newton's laws and the current position and velocity of every particle in the universe, it was possible, in principle, to predict everything for all time" (p. 19).

The term cybernetics formally appeared in 1843, in the work of Ampère to mean "the art of government" (François 1999, p. 204), and by Trentowski in a Polish book about management. Between 1854 and 1878, the French physiologist Barnard established the idea of an internal milieu, distinguishing between internal systems processes and the environment, and in 1866 the de Cyon brothers described the first example of biological self-regulation.

Building on the work of Newton, Henri Poincaré tried to move from measurements in the relationships of two objects, to measurements involving three, such as three planets in space, each exerting gravitational forces on the other. The difficulties in producing such measurements became known as the *three-body problem*, again defying the dream of perfect measurement and prediction. In the process, however, Poincaré created algebraic topology, which was necessary even for his attempts. His work also fed significantly into the field of dynamical systems, a precursor to chaos theory.

At a meeting of the International Congress of Mathematicians in 1900, David Hilbert posed a list of questions about math, itself: (1) Is mathematics complete (i.e., can every mathematical statement be proved or disproved from a given finite set of axioms); (2) Is mathematics consistent; and (3) Is every statement in mathematics decidable?

By 1930, Hilbert was confident that the answer to all three questions would be found to be "yes." At the same meeting, Kurt Gödel (just 25 at the time) presented his proof of the so-called *incompleteness theorem*. "This theorem stated that if the answer to question 2 above is 'yes' (i.e., mathematics is consistent), then the answer to question 1 (is mathematics complete?) has to be 'no'" (Mitchell 2009, p. 59). It was only later that Alan Turing negated the third question, using the same basic principles as Gödel's incompleteness proof.

The dream of a perfectly ordered and predictable universe, captured by the elegance of mathematics, had faded. Even fundamental beliefs about mathematics differed. As explained by Rosen (2012), there is a basic distinction between "mathematicians who believe that the mathematical universe pre-exists, possessing properties which must be discovered, and those who believe that the mathematical universe must be constructed or created, and that this construction is an entirely arbitrary process" (p. 59).

Parallel to these developments, the real world of humans and societies was proving to be anything but orderly. Chaos had returned.

Complexity and the Twentieth Century

The balance of this chapter is the story of three realms, each of which is defined by its own intellectual movement that created a new area of knowledge. Like feudal realms of the Middle Ages, however, they share intertwined histories. There were important individuals who knew each other and cooperated, or who competed for status. There were locations which changed hands over time, like cities won or lost in battles. In the end, some ideas prevailed and others were virtually lost – only to be rediscovered and revisited.

Systems science, cybernetics, and complexity science all began in the early twentieth century, near the time that Einstein proposed his theories of general and special relativity, and that the foundations of quantum mechanics were discovered. That era also coincided with World Wars I and II, which significantly impacted scientific research and technological developments.

World War I introduced a new level of industrial technology to battle, and World War II eclipsed that. In 1903, the airplane was still a curious experiment. By World War II, it was a military necessity, which then sparked the need for anti-aircraft technology.

World War II, particularly, created new challenges of complexity. It was no longer just a matter of moving soldiers and weapons and basic supplies (e.g., food, water, and ammunition). War machines of all kinds required fuel and maintenance. Wireless (i.e., radio) communications allowed for long-distance coordination of troops and plans, including encryption for secrecy. The intersections of warships with airplanes and ground troops, including trucks and tanks, missiles and bombs, supply routes, medical facilities, and so on, required new ways of thinking about battles. This complexity demanded new ways of calculating problems and answers.

By the end of World War II, physicists and mathematicians had proven themselves to be invaluable to the war effort, and therefore to society. These scientists were anything but esoteric or irrelevant "academics." Behavioral scientists had been integral to the war efforts as well. The Tavistock Institute in the UK included both psychiatrists and organizational specialists. Their work with the British military included everything from "shell shock" of soldiers to training and officer selection. Centers of research across the USA were established, largely through military funding, many of which remain active today. This includes the 17 National Laboratories, as well as research departments in many universities.

Many of the pioneers in cybernetics and systems science, and what would become complexity science, found themselves involved in military-related projects. Alan Turing's work in mathematics was famously applied to code-breaking of Nazi communications, as well as laying foundations for computer technologies. The development of anti-aircraft systems formed the theoretical bases for both cybernetics and system dynamics. John von Neumann worked on the Manhattan project, as well as multiple other projects for different branches of the military.

Other significant scientists were simply displaced by the chaos. This included Nicolas Rashevsky, who helped to create the field of theoretical biology, as well as Ludwig von Bertalanffy, considered to be one of the prominent theorist of General System Theory.

A relatively small number of universities and research centers became something like hubs in the network of research across all three domains. Key locations included the University of Chicago, MIT, the University of Pennsylvania, the Institute for Advanced Studies at Princeton, the University of Michigan, the State University of New York at Buffalo, the University of Illinois, Bell Labs, the California Institute of Technology, Stanford, and the Santa Fe Institute. Some places played parts in the development of all three domains; others contributed only to one, but with significance. Decisions at each of these locations affected the careers of the people involved, and the direction of the work.

Towards Complexity, Cybernetics, and Systems

There is no simple chronology or set of theoretical foundations which distinguishes the three realms from each other. This may partly be due to the diversity of those involved. John von Neumann made significant contributions in mathematics, physics, economics, computing, and statistics. Warren McCulloch studied theology and philosophy, mathematics, psychology, medicine, and neuropsychiatry. Nicolas Rashevsky was a theoretical physicist who helped develop the field of mathematical biology and who is credited with creating the first model of neural networks. Norbert Wiener was a philosopher and mathematician whose work affected engineering and computing. Alan Turing was a computer scientist, mathematician, logician, philosopher, and theoretical biologist. Ludwig von Bertalanffy studied philosophy and biology. James Greer Miller was both a medical doctor and psychologist.

Chronologically, cybernetics was the first realm to be formalized. It could be considered to be more technical than systems science (meaning related to mathematics and computers) but it came first out of neurology. Rashesvsky was shifting from theoretical physics to mathematical biology, and Bertalanffy was exploring alternatives to a physics-based biology, both by the 1930s, creating the foundations for systems science prior to the advent of cybernetics. Complexity science would emerge later, but the foundations were set long before.

An excellent and elegant summary of theories and theorists is provided by François (1999). It should be referenced as a companion to this chapter, for those interested in the history of systems and cybernetics.

Complexity

Warren Weaver played a pivotal role in the developments towards complexity science by the 1930s. While he was head of the Natural Sciences Division of the Rockefeller Foundation, he approved funding for major projects in molecular engineering, genetics, and agriculture, which led to molecular biology (see: https://en.wikipedia.org/wiki/Warren_Weaver).

Ironically, the success of molecular biology has been cited as an impediment in the development of disciplines such as systems biology. As long as physics-like, bottom-up models worked, why look further?

Weaver's own research interests centered on language and translation. In a 1947 letter to von Neumann, he suggested the possibility of using a digital computer to translate natural human language documents. This idea became a highly influential memorandum in 1949. Also in 1949, Weaver wrote a paper titled "Recent Contributions to the Mathematical Theory of Communication," which explained Shannon's theories to non-mathematical audiences.

It was another paper in 1948, however, which foreshadowed complexity science. Titled simply "Science and Complexity," he addresses the nature and history of science, problems of simplicity, and what he calls "disorganized complexity." (It is impossible to trace individual entities such as molecules, but accurate measurements can be made for large enough collectives, such as volumes of gasses.) Above that comes "organized complexity," the realm of statistics and probabilities. Finally, he explains the "boundaries of science," where science applies and where it falls out of its realm. As he concludes:

> . . .the humble and wise scientist does not expect or hope that science can do everything. . . There are rich and essential parts of human life which are alogical, which are immaterial and non-quantitative in character, and which cannot be seen under the microscope, weighed with the balance, nor caught by the most sensitive microphone (p. 10).

The end of the wars created a need for massive redevelopment of cities and economies, and of political structures on national scales. Concurrently, this required new approaches and ideas in order to match the scales of the challenges.

Cybernetics

The modern foundations of cybernetics emerged in 1942. Frank Freemont-Smith of the Josiah Macy, Jr. Foundation organized a small meeting about "cerebral inhibition," a new concept in neurology at the time. There were six invited participants: Warren McCulloch, Gregory Bateson, Lawrence Frank, Margaret Mead, Arturo Rosenblueth, and Lawrence Kubie. This was the precursor to what became the Macy Conferences on Cybernetics.

There were ten cybernetics conferences held between 1946 and 1953. Seventy scientists were involved in one or more of the meetings, ranging from physicists and mathematicians to psychologists and anthropologists. McCulloch chaired the entire series. Based on the early meetings, Norbert Wiener published the book *Cybernetics: Or Control and Communication in the Animal and the Machine*, in 1948. According to Kline (2015), "The allure of cybernetics rested on its promise to model mathematically the purposeful behavior of all organisms, as well as inanimate systems" (p. 4).

Systems

The aftermath of World War II saw a shift in investment from military spending to recovery.

The Marshall Plan was instituted in 1948, through which the USA gave over $13 billion to help rebuild the Western European economies. Also in 1948, a report was commissioned by the Ford Foundation, then the largest philanthropy in the world, outlining a five-point program that would contribute to:

1. World peace and a world order of law and justice.
2. Greater allegiance to the basic principles of freedom and democracy.
3. Economic well-being of people everywhere.
4. Improved educational opportunities.
5. Increased knowledge of factors that influence or determine human conduct, and the extension of such knowledge for the benefit of individuals and society (Hammond 2003, p. 6).

This fifth program area led to the establishment of the Center for Advanced Study in the Behavioral Sciences (CASBS), in 1954. Its "purpose was to bring together scholars in the behavioral sciences, which included biology, psychology, and the social sciences, all of these fields [which] were dramatically affected by wartime developments in technology and management" (Hammond 2003, p. 7). It was there, in the same year, that the organization which would become the Society for General Systems Research (now the International Society for the Systems Sciences) was conceived. The founders present at the time were Ludwig von Bertalanffy, Kenneth Boulding, Ralph Gerard, and Anatol Rapoport. Boulding, Gerard, and Rapaport were also instrumental in planning for the creation of CASBS. With assistance from James Grier Miller, SGSR became an affiliate of the American Association for the Advancement of Science in 1956.

Science

It is important to contrast this development with another which also came out of World War II. Vannevar Bush, an engineer and inventor, and professor at MIT, was appointed as president of the Carnegie Institution of Washington (CIW), as well as to the National Advisory Committee for Aeronautics (predecessor to NASA) in 1938.

The CIW dispersed about $1.5 million per year for research, primarily to eight major laboratories – MIT being the largest single recipient.

As noted in Zachary (1997):

> Bush wanted the institute to concentrate on hard science. He gutted Carnegie's archeology program, setting the field back many years in the United States. He saw little value in the humanities and social sciences, and slashed funding for *Isis*, a journal dedicated to the history of science and technology and its cultural influence. Bush later explained that "I have a great reservation about these studies where somebody goes out and interviews a bunch of people and reads a lot of stuff and writes a book and puts it on a shelf and nobody ever reads it" (pp. 91–95).

In 1940, Bush convinced then-president Franklin D. Roosevelt to establish the National Defense Research Committee, and in 1941, the Office of Scientific Research and Development (OSRD), where he was appointed as chair. (The OSRD oversaw the Manhattan project, amongst others.) By postwar 1947, the OSRD had been reduced to minimal staffing. It was to be replaced by the creation of the National Science Foundation, but due to political issues that was not accomplished until 1950. Clearly, though, the stamp of "hard science" had been set. It was against this definition of science that systems, cybernetics, and complexity continue to be challenged.

Cybernetics and Technology

Cybernetics began with a multidisciplinary perspective. Freemont-Smith of the Macy Foundation described this explicitly in 1949, telling the cybernetics group that one purpose of the meetings was to remove barriers between the disciplines in order to create interdisciplinary communication. In his words, the problems were urgent because the "'physical sciences have developed to such a point and have gotten so far ahead of the social sciences that there is grave possibility that social misuse of the physical sciences may block or greatly delay any further progress in civilization'" (Kline 2015, p. 39).

Achieving that intention was not so easy. Despite the fact that Gregory Bateson and Margaret Mead had worked with McCulloch to create the conferences, they were clearly dominated by the "hard scientists" from the beginning. As McCulloch explained to Freemont-Smith, he believed that a "formal, logical, or go-no-go [digital]" foundation had to first be established by mathematicians and engineers, followed by neurophysiologists (Kline 2015, p. 42). Following that, the social scientists could talk about applications. That idea determined the order of speakers at the conferences, and the hierarchy of importance became more pronounced.

At special meeting held in 1946, "Norbert Wiener flatly stated that the social sciences did not have long enough runs of consistent data to which to apply his mathematical theory of prediction" (Kline 2015, p. 37). In 1947, the group denied membership to Erik Erikson "because Walter Pitts thought he lacked rigor and logical reasoning" (p. 37). Then the mathematicians and physiologists criticized a presentation by one of the founders of Gestalt psychology because it was not grounded in neurological data.

As noted earlier, antiaircraft research during World War II significantly affected frameworks for cybernetics. According to Kline (2015):

> . . .studying human operators as links in the control systems of the plane and the antiaircraft director—that is, the pilot and the tracker—led Wiener and Bigelow, in collaboration with Arturo Rosenblueth, to realize that humans and machines could be analyzed using the same principles of communications and control engineering. . .(p. 19).

The human-computer analogy had been introduced in a 1943 paper by Rosenblueth, Wiener, and Bigelow, titled "Behavior, Purpose, and Teleology." The concepts of communication and control extended far beyond neurology, as indicated by the title of the proceedings from the conferences: "Cybernetics: Circular Causal and Feedback Mechanisms in Biological and Social Systems." Wiener's own early research, however, was focused closely on theories of information.

Claude Shannon was a key figure in the development of information theory. He worked at both MIT and Bell Laboratories. It was no small issue that Vannevar Bush, then teaching at MIT, had taken Shannon under wing, and continued to keep in contact after moving on to Washington in 1939. Shannon also worked briefly with Wiener on his doctoral studies.

Shannon's second wartime project at Bell Labs was in Project X, creating a top-secret, secure, radio-telephone system for President Roosevelt to communicate with Prime Minister Churchill. In early 1943, Turing spent two months at Bell Labs, inspecting the Project X system for the British government, talking daily with Shannon.

While at MIT, Pitts and Shannon had independently developed models of the nervous system, using different forms of mathematics. From 1944 to 1947, "Pitts worked closely with Wiener on the analogy between the digital computer and the brain, neural nets, digital nerve impulses, and multiple prediction" (Kline 2015, p. 26).

In 1948, the same year that Wiener published "Cybernetics," Shannon published "A Mathematical Theory of Communication," in the *Bell System Technical Journal*. Wiener's and Shannon's theories were basically mirror images of each other. As summarized by Kline (2015):

> Both men measured information in regard to the patterns transmitted in communication processes, whether these occurred in humans or machines. Both men bridged communication theory and physics by defining information with an equation that was similar to the formula for the physical concept of entropy, the unavailability of a system's energy to do work (p. 10).

Both Wiener and Shannon were brilliant mathematicians, but preferred different forms of mathematics. While both theories incorporated entropy, the mathematical signs were reversed. (Wiener considered the presence of information to represent negative entropy. Shannon was not concerned with the content of the information transmitted.) There was a brief discussion about using both of their names, as in the Shannon-Weaver theory, but their work was evaluated in different ways. Those differences would become much more distinct over time.

Despite the value of rigorous, mathematical models, and the brain-computer analogy, they also caused some contention within the Macy Conference meetings. By 1947, the psychologist Hans Lukas Teuber had complained to McCulloch that psychology seemed to be caught in the middle between neurophysiology and robots. Later, Ralph Gerard, a neurophysiologist, questioned the representation of the brain as purely digital (neurons as on-and-off switches), and the treatment of such analogies as if they were reality.

As described by Kline (2015), a number of key members of the meetings had strong vested interests in the digital side of the debate. The model of McCulloch and Pitts, on which much of the work had been founded, was a logical model made up of digital neurons. Von Neumann and Bigelow had used that model in their development of a computer system. Von Neumann apparently conceded that biology was more complex than this model, but still insisted on a digital representation for the ease of research. Bigelow argued similarly that mathematicians and physicists preferred to ignore the biology and focus on the digital functioning.

The debate continued into 1952 when Ross Ashby, an English cybernetician, presented his work on the homeostat. That was meant to be a model of brain behavior, showing how an organism might adapt to a new or changing environment. Ashby claimed that his clockwork mouse was similar enough to a living mouse to substitute for study. Wiener apparently agreed. Interestingly, both Pitts and Bigelow criticized the model for its lack of randomness, a trait found in actual brains. As Bigelow reportedly stated, "'It may be a beautiful replica of something, but heaven only knows what'" (Kline 2015, p. 53).

McCulloch invited Shannon to the Macy Conferences as a guest in 1950 and 1951. The topic of the 1950 meeting was language, and Shannon presented new research about quantifying redundancy. His "prediction experiment" showed that communication in English could be compressed by about 75% and still be understood. Ultimately, though, Shannon was only concerned about signal transmission. His interest was not in the content or meaning of the transmission, which limited the extent to which his theory might be applied or extended. After significant debate between the participants, Shannon reportedly explained:

> "I have never had any trouble distinguishing signals from noise because I say, as a mathematician, that this is a signal and that is noise. But there are, it seems to me, ambiguities that come at the psychological level..." [But] "that is hardly a mathematical problem. It involves too many psychological elements" (Kline 2015, p. 57).

By the end of the 1951 meeting, a newly burgeoning theory of information was overtaking the original concepts of cybernetics. Equally difficult was the failure to overcome divisions between disciplines. Wiener, in particular, was frustrated by the lack of a common language (by which he meant mathematics), especially for the social sciences. There had been thoughts of cybernetics as a universal discipline or metascience, which would “subsume other sciences through its wide applicability, support them through computerization, and reorder the physics-dominated hierarchy of science” (Kline 2015, p. 62), but that also did not materialize.

McCulloch was reportedly ambivalent, at best, about the shift towards information theory. In 1952, Wiener left the cybernetics group over personal and professional conflicts with McCulloch. That same year, Bateson visited McCulloch to discuss applications of cybernetic ideas (i.e., the introduction of logical paradoxes to computers). That discussion started Bateson’s work on his double-bind theory of schizophrenia.

Wiener’s influence on cybernetics, however, was just reaching its zenith. His 1948 book, *Cybernetics*, became unexpectedly popular. He followed that with another book in 1950, *The Human Use of Human Beings*. Wiener actively promoted his books in the popular media, which created new dilemmas as well. According to Kline (2015), the media picked up three interconnected themes: (1) that cybernetics was a new science based on the brain-computer analogy, (2) that computer-controlled factories might appear, creating unemployment, and (3) that information and feedback were basic robotic properties.

Confusion about cybernetics only increased when L. Ron Hubbard, founder of the Church of Scientology, published *Dianetics: The Modern Science of Mental Health* in 1950. Hubbard’s work was dismissed almost immediately by the American Psychological Association, and his foundation went bankrupt in 1952, after he was accused of practicing medicine without a license. Wiener had worked to distance himself from dianetics, but interestingly, Shannon appealed to McCulloch to support Hubbard’s work.

While cybernetics became more popularized, and eventually conflated with science fiction, information theory was adopted by the academic realms. Two particular meetings of note were held in 1956; one was a meeting at MIT which founded cognitive science (https://dspace.mit.edu/bitstream/handle/1721.1/52022/RLE_QPR_044_PUBREP.pdf?sequence=1), the other the Dartmouth workshop about artificial intelligence (https://en.wikipedia.org/wiki/Dartmouth_workshop). Shannon and McCulloch attended both meetings, along with numerous other luminaries at each. John McCarthy, one of the organizers of the Dartmouth workshop, explained that he had purposefully invented the term “artificial intelligence” in order to distance any association with cybernetics. Bell labs made a similar distinction in 1960. By contrast, a seminar was sponsored in 1956 by the Oak Ridge National Laboratory on Information Theory in Biology, explicitly applying the Shannon-Wiener theory and noting applications of General Systems Theory (https://archive.org/details/symposiumoninfor00yock).

Hienz von Foerster, a participant who also edited the proceedings from the Macy Conferences, established the Biological Computer Laboratory at the University of Illinois in 1958. This was done through funding from the Office of Naval Research, the US Air Force, and the National Science Foundation. McCulloch consulted with the BCL, and W. Ross Ashby joined it in 1961. Military interest was in the area of bionics; models of biological systems which might help to solve problems of reliability in complex electronic systems. In 1963 alone, the military invested $100 million in bionics research (Kline 2015).

While cybernetics was on the wane amongst scientists in the USA, government interest continued for a time. Cybernetics had taken hold in the Soviet Union, and there was concern that the US might be falling behind. In 1964, the CIA helped to organize the American Society for Cybernetics (ASC). At the direction of President Kennedy, a cybernetics panel was convened under the President's Science Advisory Committee. These connections and attention helped to reinvigorate the ASC, and cybernetics.

In 1965, the Institute of Electrical and Electronics Engineers (IEEE) established a group on Systems Science and Cybernetics (SSC). W. D. Rowe, the first chair of the SSC, distinguished the two domains as follows:

> "Systems Science participants [in the SSC] approach problems from an optimization point of view, i.e., the system is described analytically by a set of cause and effect relationships whose parameters can be varied to optimize a particular measure of effectiveness. Cybernetics participants approach the same problems in terms of models (real or postulated) of natural systems, systems whose variables are not readily describable in analytic terms" (Kline 2015, p. 190).

Von Foerster first proposed the term *second-order cybernetics* in an ASC presentation in 1974. Roots of the concepts, though, dated back to the work of Humberto Maturana, at McCulloch's MIT laboratory, in the late 1950s – which became the theory of autopoiesis.

This turn only further alienated traditional scientists. Wiener and von Neumann had opposed any extension of cybernetics or related theories into larger realms, such as the social sciences, to the end. Military funding had already fallen dramatically. McCulloch's group at MIT virtually disbanded after his death in 1969, and the BCL closed in 1973.

According to Kline (2015):

> The cybernetics moment began when [cybernetics and information theory] emerged shortly after World War II, reached its peak with their adoption and modification in biology, engineering, the social sciences, and popular culture in the 1950s and 1960s, and ended when cybernetics and information theory lost their status as universal sciences in the 1970s (p. 6).

Systems Science

The history of systems science, specifically as embodied in the Society for General Systems Research (SGSR) and its successor, the International Society for the Systems Sciences (ISSS), has been well-documented by Hammond (2003).

The University of Chicago had long been a center for interdisciplinary research in the social sciences. According to Hammond (2003), Robert Maynard Hutchins, president and chancellor from 1929 to 1951, did a great deal to foster the interdisciplinary and innovative approaches that were used. And interestingly, every founder of the Society for General Systems Research (the professional organization of the systems sciences) spent time at the university in those early days.

Nicolas Rashevsky was a theoretical physicist who had immigrated to the USA in 1924. (He had completed his Ph.D. in theoretical physics before he was 20.) He initially worked for Westinghouse Research Laboratories, which is where he became interested in biology. His first year at the University of Chicago was through a Rockefeller Fellowship for a project on physico-mathematical methods and biological problems, which Warren Weaver helped to arrange.

In 1935, Rashevsky was appointed Assistant Professor of Mathematical Biophysics in the Department of Psychology, moved for a short time into the Department of Physiology, and in 1937, was allowed to establish an independent group on mathematical biophysics. By 1947 he was a full professor and had created an independent Committee on Mathematical Biology (Abraham 2004).

According to Abraham (2004), Rashevsky's work in biology was controversial from the beginning. Even within physics, he was considered to be more of a mathematical physicist than a theoretical physicist. He saw no reason to present testable theories, or to subject his work to experimentation. Further, he had no background or experience in biology, or in methods of biological experimentation. His interest was in purely theoretical models. His lack of experience in biology was also a barrier to both the understanding and the acceptance of his work by those in the field. Despite the difficulties, however, Rashevsky had a significant impact on what would become systems science.

Notably, Ludwig von Bertalanffy visited the University of Chicago from 1931 to 1933 on a Commonwealth fellowship and returned from 1937 to 1938 on a Rockefeller fellowship. It was there, in a 1937 seminar, that he introduced his concept of a general system theory.

Parallel to the work of Rashevsky and Bertalanffy was that of James Greer Miller. Miller had degrees in psychology and psychiatry from Harvard, where he had worked closely with Alfred North Whitehead. Miller moved to the University of Chicago in 1948 and in 1949 created the Committee on Behavioral Sciences, which included Ralph Gerard and Anatol Rapaport (a mathematical biologist who also worked closely with Rashevsky). According to Miller [video], it was Enrico Fermi who prompted him to work towards a general theory of science, particularly as applied to human issues.

Gerard and Rapaport both started as students at Chicago and later became faculty members. Gerard (entering at the age of 14) had trained in neurophysiology, but associated with the ecologists at the university. He also worked closely with Paul Weiss in the biology department. In a statement outlining his research interests for the CASBS, "he wrote that he was interested in facilitating greater communication between the fields of physiology, psychology, psychiatry, and sociology" (Hammond 2003, p. 146). He contributed to the early development of psychoanalysis, as well as working on issues about the role of science in society – including ethics. He was one of the participants in the Macy Foundation cybernetics conferences.

Rapaport joined Rashevsky's Committee on Mathematical Biology in 1947, where he eventually became an assistant professor mathematical biology (Hammond 2003). One of his assignments involved proof-reading a paper by Rashevsky, "which became a catalyst for Rapaport's own work in game theory" (Hammond, p. 156). Rapaport was seminal researcher in, and a co-author of the book titled, *Prisoner's Dilemma*. He developed mathematical models of biological and sociological processes which included applying neural network models from McCulloch and Pitts to phenomena such as the spread of disease, and the spread of rumors. He was also a core member of Miller's Committee on the Behavioral Sciences. He worked closely with Kenneth Boulding, an economist who was also highly instrumental in the formation of the SGSR.

McCulloch became a frequent visitor to the Committee on Mathematical Biophysics. It was there that he met Walter Pitts, a teenager who had started attending classes, and ended up in Rashevsky's committee, by the time that he was 15. In 1943, McCulloch and Pitts published their now-famous paper, "A Logical Calculus of the Ideas Immanent in Nervous Activity." It set the foundations for cybernetics, as well as artificial intelligence. That same year, Pitts joined McCulloch and Norbert Wiener as a graduate student at MIT.

In order to promote his program, Rashevky established a new journal in 1939, the "Bulletin of Mathematical Biophysics." It was primarily an outlet for his own papers, and those of his students, but was also the journal in which the famous 1943 paper by McCulloch and Pitts was published, as well as subsequent papers by them (e.g., "How We Know Universals," in 1947).

By 1948, funding for Rashevsky's program was getting difficult, and the university was concerned about putting more students into the program (Abraham 2004). Hutchins stepped down as chancellor of the university in 1951. More problems surfaced in 1954 when the House Un-American Activities Committee (established to search for Americans with Nazi, and later communist, connections) targeted several of Rashevsky's faculty members, including some on the dissertation committee of Robert Rosen. McCulloch helped to get a letter published in *Science*, in 1956, signed by eight scientists in total, expressing outrage at the accusations.

Rosen (1972) remembered the internal process quite differently. The departure of Hutchins had much to do with changing the image of the university, due to political pressures. Rashevsky was pressured to get rid of his faculty members who fell under suspicion, even without proof of wrong-doing, which he refused to do. By 1960 a new university president and new dean of the program were once again supporting Rashevsky. It was a conflict about Rashevsky's successor, after his retirement, which led Rashevsky to resign just months before his retirement date. (Rashevsky wanted a long-time internal member of the committee, and the dean insisted on an external candidate.)

The congressional investigations affected not just Rashevsky's program. Hutchins' departure has already marked a significant change in the university climate, and in 1955 Miller, Gerard, and Rapaport, along with others in Miller's program, moved *en masse* to the University of Michigan at Ann Arbor, where Boulding was already in residence. According to Miller [video], this came through an amicable agreement between the university presidents, after the University of Michigan offered to fully fund the program. Rashevsky resigned from the University of Chicago in 1964 and also moved to Michigan.

According to Miller (1978), his 1051-page tome, "Living Systems," was conceived in 1949, the year that he coined the term "behavioral science." He began regular committee meetings to discuss systems concepts in 1952, moving them with him from Chicago to Michigan and beyond. He completed his book 5 years after taking the presidency of the University of Louisville, in Kentucky. According to Hammond (2003), he established the Systems Science Institute, one of the largest systems programs in the country, before leaving there in 1980. By 2015, the program had long disappeared, and Miller's archives at the university contain no mention of his work in systems science.

International Society for the Systems Sciences

As noted earlier, the Society for General Systems Research (SGSR) was formed by collaborations between noted scientists around 1954. Its affiliation with the American Association for the Advancement of Science was significant in attaching its identity to larger scientific communities. Ironically, the transition to the ISSS, in 1988, also came with the society's separation from the AAAS, but not without significant internal conflicts.

There were numerous "aims" of the society at the time that it was formed, and not all were in close agreement. As still stated on the organization's website:

> The initial purpose of the society was "to encourage the development of theoretical systems which are applicable to more than one of the traditional departments of knowledge," with the following principal aims:
>
> - To investigate the isomorphy of concepts, laws, and models in various fields, and to help in useful transfers from one field to another.
> - To encourage the development of adequate theoretical models in areas which lack them.
> - To eliminate the duplication of theoretical efforts in different fields.
> - To promote the unity of science through improving the communication among specialists (http://isss.org/world/about-the-isss).

Some members were adamant that the work of the society should be defined by science. Others were more management- and practice-oriented and found the strictures of traditional, physics-based science to be confining, if not in opposition to the intended purposes.

Bertalanffy (1968) defined three "aspects" of systems theory. *Systems science* is the "scientific exploration and theory of 'systems' in the various sciences (e.g. physics, biology, psychology, social sciences), and general system theory as doctrine of principles applying to all (or defined subclasses of) systems" (p. xix). *Systems technology* is the realm of "problems arising in modern technology and society, comprising both the 'hardware' of computers, automation, self-regulating machinery, etc. and the 'software' of new theoretical developments and disciplines" (p. xx). Finally, *systems philosophy* refers to the "reorientation of thought and world view ensuing from the introduction of 'system' as a new scientific paradigm (in contrast to the analytic, mechanistic, one-way causal paradigm of classical science)" (p. xxi).

Members who demanded that systems remain committed to, and focused on, science, remained clearly in Bertalanffy's first definition. They worked in universities and published in academic journals. Their intentions were to affect existing scientific disciplines through the discovery of commonalities across the domains, or even isomorphies which would connect theories in different domains. Some insisted that theories be presented using mathematical formalisms.

Other members worked in the social sciences, including economics and management. C. West Churchman significantly influenced the society through his emphasis on ethics and organizations. Churchman had been a student of E. A. Singer in philosophy and applied his work to the study of management, amongst other disciplines. By the 1980s, discussions about the distinctions between "hard" and "soft" systems were shaping internal divisions. Hard systems were based on traditional, empirical science. Soft systems recognized the importance of humans as part of the systems in question, both as observers and participants who affected systems, as well as interpreters who could never be entirely objective. (This was similar to second-order cybernetics.) The extreme position came from "critical systems," based on the philosophy of the Frankfurt school and a focus on emancipation as a necessary part of addressing unequal levels of political power.

Bertalanffy's (1968) systems technology was captured largely in terms of practice-oriented applications, such as organizational or management consulting. There was little connection to computer systems or information technology.

Systems philosophy was the most difficult. Taken to an extreme, it challenged some of the fundamental tenets of traditional science. Bertalanffy (1968) pointed specifically to influences ranging from the process philosophy of Whitehead (1978) to Gestalt theory, among many others. One of the most apt descriptions about the differences may actually be a statement from Brian Arthur, in which he was talking about complexity rather than systems, per se. As he said, "The Newtonian clockwork metaphor is akin to standard Protestantism. Basically there's order in the universe. . . It's that God has arranged the world so that the order is naturally there if we behave ourselves" (Waldrop 1992, p. 330). As he continues,

> The alternative—the complex approach—is total Taoist. In Taoism there is no inherent order. The world started with one, and the one became two, and the two became many, and the many led to myriad things. The universe in Taoism is perceived as vast, amorphous, and ever-changing. You can never nail it down. The elements always stay the same, yet they're always rearranging themselves. So it's like a kaleidoscope: the world is a matter of patterns that change, that partly repeat, but never quite repeat, that are always new and different (Brian Arthur, as quoted in Waldrop 1992, p. 330)

Bertalanffy never seemed to have a problem with all three aspects being parts of one unified concept. The society, however, never seemed to be able to bridge the distinctions.

The Santa Fe Institute

While cybernetics had strong foundational ties with information technology (IT), there was parallel work taking place which affected the developments more directly. This set of connections begins again with John von Neumann.

At the end of his life in 1954, von Neumann had begun working on the concept of "cellular automata." As explained by Mitchell (2009), von Neumann's self-reproducing automaton involved a dual use of information. It "contained not only a self-copying program but also the machinery needed for its own interpretation. Thus, it was truly a self-reproducing machine" (loc. 2007). This dual use of information was considered the key to the way that DNA replicates itself and was also the central to Turing's proof of the undecidability of the Halting problem in computers. (Both Turing and von Neumann had tried to develop "general theory of information processing that would encompass both biology and technology" (loc. 2054). The dual use of information was also present in Gödel's incompleteness theorem.

A 1946 paper by von Neumann, Burks, and Goldstine titled "Preliminary Discussion of the Logical Design of an Electronic Computing Instrument," was considered foundational to the field of computer science (Waldrop 1992). Arthur Burks, a philosopher and expert in the work of C. S. Peirce, completed the work that von Neumann had started on cellular automata.

George Cowan (to be distinguished from Jack Cowan) was a student at Princeton in 1941 when he began working with Eugene Wigner on chain reactions in uranium. In 1942, he, Wigner, and others moved to the Metallurgy Lab at the University of Chicago, to work with Enrioco Fermi, where the first atomic pile was being developed, work which became part of the Manhattan Project.

Following World War II, with a PhD in physical chemistry, George Cowan returned to work at the Los Alamos National Lab. The concept for the Santa Fe Institute (SFI) began in 1956 (https://www.santafe.edu/about/history).

John Holland was a graduate of MIT and an employee at IBM. In 1952, he attended a lecture about the theories of learning and memory by neurophysiologist Donald Hebb. Hebb had published his ideas about the brain in 1949 in his book, *The Organization of Behavior*. His hypothesis was that "synapses" (points of connection in nerve cells) were constantly changing, creating the basis of learning and memory. As described by Waldrop (1992):

> …a network that started out at random would rapidly organize itself. Experience would accumulate through a kind of positive feedback: the strong, frequently used synapses would grow stronger, while the weak, seldom-used synapses would atrophy. The favored synapses would eventually become so strong that the memories would be locked in. These memories, in turn, would tend to be widely distributed over the brain, with each one corresponding to a complex pattern of synapses involving thousands or millions of neurons (p. 158).

This led to Hebb's second assumption, that the brain eventually organized itself into "cell assemblies"; thousands of neurons through which impulses would continue to circulate and reinforce patterns.

Excited about what he had heard, Holland decided to try programming a "neural network simulator" on the IBM computer (an IBM 701, with four kilobytes of memory.) He and the team leader modeled neurons as "nodes" (tiny computers with memory of their internal states) and synapses as abstract connections between the nodes, even including varying strengths of the connections. Their first paper about the results was published in 1956.

Holland left IBM in 1952 to begin a Ph.D. in mathematics at the University of Michigan, where he met Arthur Burks. Burks brought Holland into his Logic of Computers group, and soon into the new Ph.D. program which became Computer and Communication Sciences. The intention was to include courses such as biology, linguistics, and psychology, in addition to information theory. By contrast, Michigan, like most post-World War II mathematics departments, was dominated by ideas from the French Bourbaki school, "which called for research of almost inhuman purity and abstraction" (Waldrop 1992, p. 162).

Holland completed his Ph.D. in 1959, with his dissertation on, "Cycles in Logical Nets." There, he proved many of the same theorems with which Stuart Kauffman found himself struggling four years later.

Holland continued to work on his evolutionary models, running into very similar "number problems" as would Kauffman. Seaweed, for example, has about 1000 genes. (Humans and most other mammals have about 100 times that many genes.) If every different possible combination of seaweed gene creates a slightly different level of fitness, then natural selection would have to work through 2^{1000} (i.e., 10^{300}) possible variations to find the "most optimal" species of seaweed. Nature simply cannot work quickly enough to make that happen.

Holland eventually arrived at a theory of emergence and hierarchy; that there must be a process through which nature used essential "building blocks" in order to produce increasingly complex systems. His solution was that sexual reproduction created the exchange of genetic material which created the building blocks he was seeking. When he put this together into his models, the result, according to Waldrop (1992), was that:

> By the mid-1960s. . .Holland had proved what he called the schema theorem, the fundamental theorem of genetic algorithms: in the presence of reproduction, crossover, and mutation, almost any compact cluster of genes that provides above-average fitness will grow in the population exponentially (p. 174).

In 1975, Holland condensed two decades of work into his book, *Adaptation in Natural and Artificial Systems*. It connected deep relationships between learning, evolution, and creativity, including his genetic algorithm. It was met with resounding silence. According to Waldrop (1992), this was primarily because "he simply didn't play the game of academic self-promotion" (p. 175).

Holland returned to idea of adaptive agents as playing games of survival with their environments. Two essential properties, he decided, were involved: prediction and feedback. To get where he wanted to go, Holland had to move past the idea that prediction was only done through human conscious or mental models. According to

Waldrop (1992), Holland's idea was that: "'All complex, adaptive systems—economies, minds, organisms—build models that allow them to anticipate the world'... Yes, even bacteria" (p. 177). Holland extended this idea further, into corporations where there are "standard operating procedures," as well as to DNA and human cultures, both of which he saw as "implicit models" to guide behavior.

In order to allow for emergence in his agents, and to avoid predetermined notions of meaning in the symbols, Holland chose to call the rules in his model "classifiers."

> In his classifier systems, the meaning of a message would have to emerge from the way it caused one classifier rule to trigger another, or from the fact that some of its bits were written directly by sensors looking at the real world. Concepts and mental models would likewise have to emerge as self-supporting clusters of classifiers, which would presumably organize and reorganize themselves in much the same way as autocatalytic sets (Waldrop 1992, p. 184).

His model ultimately created an "open marketplace" for classifiers, in which, as they competed against each other for fitness, connections were strengthened or weakened, as in Hebb's theory. This part of the model became known as the "bucket brigade," for the ways in which the strengthening of connections (like synapses) passed directly from one classifier to another. In order to deal with distinctions between exploration and exploitations, Holland brought back his genetic algorithms.

In 1980, Holland began collaborating with two psychologists, Keith Holyoak and Richard Nisbett, and the philosopher Paul Thagard, working towards a general theory of learning. They came up with three principles that mirrored the basic tenants of Holland's classifier system:

> ...namely, that knowledge can be expressed in terms of mental structures that behave very much like rules; that these rules are in competition, so that experience causes useful rules to grow stronger and unhelpful rules to grow weaker; and that plausible new rules are generated from combinations of old rules (Waldrop 1992, p. 193).

This defined what Holland meant by an "internal model."

In the early 1980s, George Cowan was invited to serve on the White House Science Council, under President Reagan. As a physicist, he was familiar with science, but not with politics. He asked advice from his friend David Packard (of Hewlett-Packard). Packard's advice was to "study their agenda" (i.e., to focus on their interests, not just his own).

George Cowan was also concerned about the gap between scientists and others that C. P. Snow had described in his paper, "The Two Cultures." Cowan appears to have thought in ways that were similar to McCulloch. He understood the realities of science, but he also saw the limitations. "'You look for the solution of some more or less idealized set of problems, somewhat divorced from the real world, and constrained sufficiently so that you can find a solution,' he says" (quoted in Waldrop 1992, p. 60). The first problem with that approach is that it had led to the continued fragmentation of science. The second was that, in the real world, everything was connected to everything else, and required a more *holistic* approach (though he disdained that term). Cowan had a sense that there were deep connections in science that should match the deep connections of the universe.

In 1982, George Cowan began gathering a group of senior scientists for weekly discussions about major issues facing science. A general consensus started to emerge about creating a PhD-granting institute with renowned faculty and collaborators. It would have no departments and would address problems that cut across disciplines, such as human behavior and cognition.

David Pines, a physicist from the University of Illinois at Urbana-Champaign, was invited to join in 1983. He contacted Murray Gell-Mann at Caltech, who was excited about the prospects. Apparently, Gell-Mann had long wanted to tackle problems such as the rise and fall of ancient civilizations, and the sustainability of current civilization. Those were not topics of interest to Caltech.

SFI was officially founded in 1984. A key part of the strategy was to invite the most renowned scientists that they could find; Nobel Laureates, McArthur Genius Award recipients, and so on. If successful, the notoriety would also attract money.

A reluctant participant to join was Philip Anderson, 1977 Noble Prize winner for his research in condensed-matter physics. He knew of Gell-Mann's work, but was skeptical about how interdisciplinary SFI might actually be. Much of his own career had been spent at Bell Labs (like Shannon), which he considered to be inherently interdisciplinary. Even the Institute for Advanced Study at Princeton was, in his view, a poor example by comparison. He had published a short article in *Science*, in 1972, titled "More is Different," explaining the concepts of "broken symmetry" and emergence. As he stated there:

> The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe. In fact, the more the elementary particle physicists tell us about the nature of the fundamental laws, the less relevance they seem to have for the very real problems of the rest of science, much less society (p. 393).

Despite the notoriety and brain-power of the scientists being attracted, getting the institute started was still challenging. Gell-Mann was one of the first to voice the realities of funding the kind of organization they were envisioning. As he explained, getting funding for cross-disciplinary research was a challenge. "If a physicist and a biologist wanted to work together, they would have to request funding from either the physics or biology department. Government agencies weren't going to fund an institute without a track record" (https://www.santafe.edu/about/history).

Holland's first introduction to SFI was in 1985, at a conference titled Evolution, Games, and Learning. (It was also the meeting where Stuart Kauffman, Doyne Farmer, and Norman Packard presented their work on autocatalytic sets.) Holland's presentation was enthusiastically received, to the point that Gell-Mann invited him to join SFI's advisory board. In 1986, SFI sponsored a conference on complex adaptive systems, featuring Holland. It was also the year that Holland co-authored the book, *Induction* explaining the principles of his classifier system.

In 1987, the focus at SFI had turned to economics. This shift had happened serendipitously rather than purposefully. John Reed at Citicorp was interested and willing to help sponsor the work.

Brian Arthur, an economist from Stanford, started one of the first important meetings at SFI with a presentation titled, "Self-Reinforcing Mechanisms in Economics." Holland's presentation followed, titled "The Global Economy as an Adaptive Process," in which he explained that the economy is actually a complex adaptive system. The ideas paralleled those which Arthur and Kauffman had been discussing, in terms of autocatalytic sets, but in different terms. Arthur and Holland ended up running a full research program together at SFI the following year.

The morning after the economics meeting, Arthur and Holland left together for Los Alamos, to attend an Artificial Life Workshop. It had been put together by Chris Langton, now a post-doc at Los Alamos, and a former student of Burks and Holland.

Working on his own, Langton had written a general-purpose cellular automaton program on his home computer. He eventually found a rule table which created a pattern something like the growth of a coral reef. "He had created the simplest self-reproducing cellular automaton ever discovered" (Waldrop 1992, p. 221).

Langton later found the work of Stephen Wolfram, a child prodigy in physics and math from England. Wolfram got his Ph.D. in particle physics at Caltech in 1979, when he was 20, and joined the faculty soon afterwards. In 1984 he moved to the Institute for Advanced Study at Princeton and shifted his focus from physics to cellular automata. He was interested in the similarities between cellular automata and nonlinear dynamical systems, at a deep mathematical level. Of particular interest to Langton was the four universal classes into which Wolfram had been able to group cellular automata.

The rules in Wolfram's Class I were basically dead ends. Within a few time steps, the process would come to a stop. Class II would progress further, but only to the point of creating a set of static groups, then halt. Class III produced the opposite results. There was perpetual movement which never settled into any stable patterns; in effect, chaos. Class IV were rare, but the most interesting. They were the rules much like in the Game of Life. There was continued movement, but with patterns of coherence. This was the edge of chaos, or complexity. (Class IV rules turned out to align with second-order phase transitions in physics.)

It was at a meeting about cellular automata at MIT, in 1984, that Langton met Doyne Farmer, who (as noted) was working with Stuart Kauffman on autocatalytic sets. Farmer invited Langton to the 1985 meeting at SFI, where Holland (who was on Langton's dissertation committee) was the featured presenter. In 1986, Langton moved to a postdoctoral position at Los Alamos.

Commonalities and Differences

There is no simple way to trace how the people, ideas, and decisions that helped to shape systems, cybernetics, and complexity intertwined – much less their relations to Western science as a whole. Two key figures have been chosen because of the ways in which they embody many aspects of the history: Robert Rosen and Stuart Kauffman. They knew each other, and their professional lives overlapped, but they never worked together. Their careers crossed locations, but at different times. They knew a number of the same important people but had different experiences of them. In their own ways, they represent many of the questions about what we know, and how we know things, in science – most specifically in the realm of biology.

As a child growing up in Brooklyn, NY, Robert Rosen knew early on that he wanted to become a biologist (Rosen 2006). By the time he was in high school, he had developed a proficiency in experimental biology. As he asked deeper questions, he moved into physical chemistry, then physics, and then mathematics. Following a somewhat winding path, he ended up as a graduate student at the University of Chicago because of his interest in their mathematics department. It was there that he met Nicolas Rashevsky, who convinced him to join his Committee on Mathematical Biology (effectively, Rashevsky's doctoral program) in 1957. It was a perfect fit for Rosen's interest in a theoretical understanding of biology.

Stuart Kauffman started as an undergraduate at Dartmouth with aspirations to become a playwright, but then decided to become a philosopher. After graduating from Dartmouth, he went to Oxford on a Marshall Scholarship, studying a program called Philosophy, Psychology, and Physiology. From there, he decided to go into medicine. In 1963, he moved to Berkeley, CA, to complete a year of preparatory work before starting medical school at the University of California, San Francisco.

Kauffman took his first course in developmental biology at Berkeley, where he also came across the work of Jacob and Monod, on genetic circuits (finding that genes can act as "switches," turning each other on and off). He had studied neural circuitry extensively at Oxford, which led him to his own experiments in the search for a genetic regulatory system which could occur spontaneously. His experiments yielded a computer model showing spontaneous order, which he sent to Warren McCulloch at MIT. McCulloch and Pitts (1943) had developed their own models of neural networks, showing mental activity as a form of information processing.

Rosen had his own encounter with Monod, but it went quite differently. As Rosen described it (2006), he attended the International Biophysics Congress in Paris in 1964. There, Monod presented his concept of operons (functional genetic units) which could explain differential gene expression (just as used by Kauffman). Monod proclaimed, though, that no theory of them existed yet. After the talk, Rosen approached Monod and explained that he had "shown that the simple 'operon networks' proposed by Jacob and Monod to explain differentiation were *identical* with the two-factor nets Rashevsky had published decades earlier" (p. 29). Monod listened briefly, then exclaimed that he was not an embryologist, and stormed off.

On the surface, it might appear that Rosen and Kauffman were pursuing nearly parallel interests; and in many ways, they were. Their choices of approaches, however, significantly affected their work. Rosen's focus on mathematics kept his progress in a theoretical realm, for reasons that he considered to be important. By choosing to go into medicine, Kauffman took an applied professional approach, though much of the work for which he would become known was also quite theoretical. With these first connections in place, it is important to step back and explain the foundations on which they were building.

Tracing back, it was at Berkeley, in 1963 that Kauffman took his first course in developmental biology and became fascinated with cell differentiation. From that came a question which would propel him into the future: “Can the vast, magnificent order seen in development conceivably arise as a spontaneous self-organized property of complex genetic systems?” (Kauffman 1990, p. 300).

Researchers were already discussing cell development as if it occurred almost exactly like the step-by-step execution of a computer program. From 1961 to 1963, Jacob and Monod were publishing their work on genetic circuits, the work for which they would later receive a Nobel Prize. This showed that any cell contains a number of regulatory genes which can turn each other on and off.

Kauffman knew, though, that in living cells, many regulatory genes could be active at once. He also knew of the work of McCulloch and Pitts, representing neural circuitry in the same binary fashion. His interest was in the stable patterns that must be developing. It was an order not preprogrammed into the genes, but an order that came from a spontaneous, self-organizing property, arising from the structure of the network.

The first problem was simply the number of states involved. If one gene has two possible states (on and off), then a network of two interacting genes has four states, three genes has eight states, etc. Real networks in real cells involve *tens of thousands* of genes.

Fortunately, there was a computer department at Berkeley in 1965. His program modeled a network with 100 genes (yielding one million trillion trillion possible states: 1,000,000,000,000,000,000,000,000,000,000.) The program ran in just 10 min, and rather than exhibiting pure randomness, the network quickly settled and oscillated through cycles of only about 10 states, on average. He had found his self-organizing order.

During his junior year of medical school, Kauffman wrote to McCulloch, explaining what he had done to develop his genetic network model. The reply from McCulloch was effusive. “All Cambridge excited about your work,” he wrote (referring to MIT in Cambridge, MA). The medical school encouraged a three-month external experience for junior-year students, so Kauffman moved to MA and lived with McCulloch and his wife. McCulloch introduced Kauffman to Marvin Minsky, who helped him run simulations computers known then as Project MAC: Machine-aided Cognition. It handled thousands of simulated genes. In 1967, Kauffman and McCulloch co-authored the paper, “Random Nets of Formal Genes.”

Rosen spent about 10 years in total at Chicago, starting as a student and finishing as an assistant professor. He moved from there around 1967 to the Center for Theoretical Biology at the State University of New York at Buffalo, where he created and ran a program in biomathematics. It was in Buffalo that Rosen met Bertalanffy when he joined the university in 1968, the year that Bertalanffy published his book *General System Theory*.

Jack Cowan was a neurophysiologist who had been McCulloch's research assistant in the 1950s and 1960s. Kauffman was introduced to him in the living room of McCulloch's house. Jack had been drawn to von Neumann's work on how reliable computers could be built from unreliable elements, as well as to that of McCulloch and Pitts. While at MIT, he took courses from Shannon and interacted with Wiener. At age 33, Jack Cowan had just been hired to head and rejuvenate the department of theoretical biology at the University of Chicago, the program that Rashevsky had founded and led.

Jack Cowan and others invited Kauffman to his first scientific conference in 1967, on Lake Como in Italy. It was there that Jack Cowan invited Kauffman to join the faculty of his new department at the University of Chicago.

McCulloch had warned Kauffman early on that it would take 20 years for biologists to understand the importance of what was being achieved. The late 1960s saw the birth of molecular biology. As described by Kauffman (1990):

> Enveloped by the Darwinian world view, whose truths run deep, held in tight thrall by the certainty that the order in organisms resides in the well wrought details of construction and design, details inevitably *ad hoc* by virtue of their tinkered origins in the wasteland of chance, molecular biologists had no use for heady, arcane, abstract ensemble theories. The birth of complexity theory, or this strand of it, though noted, received no sustaining passion from its intended audience (p. 304).

Cowan's own work continued in the theoretical neurology he had started under McCulloch. Five years after moving to Chicago, he collaborated with a postdoctoral student, Hugh Wilson, and together they created what became the Wilson-Cowan equations. These captured large-scale brain behavior using differential equations rather than Boolean algebra. As Jack Cowan explained in an interview in 2018:

> . . .it took almost. . .30 to 40 years for the neuroscience community and others to catch up to the equations but now everybody uses them, and they work like a charm. As I mentioned before, they're the right equations, and if you have the right equations it makes things a lot easier. . . What's lacking in a lot of brain research is there's no framework and we provide this framework (https://www.youtube.com/watch?v=7Ht9k824nWA, min. 06:16 – 07:00).

After arriving at Chicago, Kauffman began pondering theories about life emerging from a "primordial soup." The problem was assuming that it happened only by random accident. Wasn't it likely that some other process, some pattern of order, was involved? What if, rather than pure, random reactions, there were catalysts involved to speed up the reactions? From this emerged a theory of autocatalytic sets, a series of reactions in which as one molecule was formed, it became the catalyst for the next, and after enough steps the whole process self-enclosed. As summarized in Waldrop (1992):

> Any given molecule participating in the autocatalytic set would have looked pretty much like any other molecule. The essence was not to be found in any individual piece of the set, but in the overall dynamics of the set: its collective behavior (p. 123).

Kauffman's genetic regulatory network mirrored nonlinear dynamics in physics. The stable cycles into which the many possible reactions would settle were like "attractors." If Kauffman's theories were correct, they could possibly offer a new explanation for the origins of life. There would not have to be a pre-existing "design," nor would nature have to rely on purely random accidents.

Kauffman (1990) later summarized the importance of this finding:

> We must, in fact, revise our view of life. Complex molecular regulatory networks inherently behave in two broad regimes separated by a third phase transition regime. The two broad regimes are chaotic and ordered. The phase transition zone between these two comprises a narrow third complex regime poised on the boundary of chaos (p. 300).

At the time, however, Kauffman found himself at an impasse. His models worked, but at this point they were still just calculations and computations. Theorists and mathematicians held sway in physics and economics, but pure theorizing was not enough in biology. That is exactly what got Rashevsky, and his students like Rosen, dismissed from the University of Chicago. This all came to a head when Stuart Rice, a renowned theoretical chemist, visited the theoretical biology lab. When asked, Kauffman explained what he had been working on. Rice's reply was simply, "Why are you doing that?" It derailed Kauffman's work for a decade.

It seemed clear that if Kauffman was to make headway, he would have to also prove his work in the laboratory. There was no simple route to test the ideas that he had been developing, but this was a moment much like his decision to move from philosophy into medicine. He needed both the ideas and the grounding.

Kauffman threw himself into learning experimental biology, focusing on *Drosophila melanogaster*, the fruit fly. In 1973, that work took him to the National Institutes of Health, near Washington, D.C., and then in 1975 to the University of Pennsylvania.

Rosen's program in Buffalo was closed in 1975. He took an appointment as the Killam Professor at Dalhousie University in Halifax, Nova Scotia (which he referred to as being like a five-year sabbatical) (Rosen 2006). His final book, *Life Itself*, was published in 1991.

Rosen began his work much like a modern Descartes. He did not want to simply accept existing assumptions. As his daughter, Judith, summarized it, his approach:

> …was to not only scrutinize each dictum that was offered as a given in any of these disciplines, but look all the way back at what the original creator of the dictum was trying to accomplish and then follow the logic (or "illogic") of the origins of it. He did this with many of the accepted traditions in science. What he discovered by doing so is that a large number of the seemingly ironclad tenets, or rules, of science were merely habits based on flawed premises (Rosen 2006, p. 33).

Rosen (2006) assumed for some time that he would find the connections between "rocks and life" in quantum mechanics, as did many other scientists. As he states, he "had long been puzzled by the fact that the state spaces they posited for every material system were mathematically indistinguishable," such that "the perceptible differences between material systems must thus lie only in a 'choice of co-ordinates'" (p. 11). By 1959, this has led him to the conclusion that:

> . . .whatever else Quantum Mechanics say, it asserts that "information" about any material phenomenon consists of observables evaluated on states. Hence, *a fortiori*, "genetic information" must be of that character too, and this must provide the material, physical basis of the formal "coding schemes" which then so preoccupied everyone (p. 12).

Ultimately, he concluded that quantum theory was much larger and more general than quantum mechanics. This explained why the Second Law of Thermodynamics did not apply to what Bertlanffy had described as an "open system." In Rosen's view, physics was actually a specialized (i.e., more restricted) area of science than biology, not vice versa. By way of example, Rosen (2006) explained:

> . . .just as the "closed system" is too impoverished, too special, to be a basis for (say) the physics of morphogenesis, exactly so is the simple system, one which can be described entirely as software to a machine, too impoverished to accommodate the living (p. 18).

This did not equate, however, with his understanding or use of mathematics. As he stated, "I rather believe that the corpus of mathematics is the only other thing which shares the organic qualities of life, and provides the only hope for articulating these qualities in a coherent way" (Rosen 2006, p. 24).

Rosen's insistence on theoretical and mathematical biology, rather than experimental work, created both alignments and divisions. He found a strong connection, for instance, with Bertalanffy and General System Theory. He did not find such an easy connection with the society that was founded on GST.

In 1962, Rosen was asked to allow some of his early papers to be reprinted in the SGSR Yearbook (which substituted as the journal of the society). He was unimpressed with most papers that he found in the Yearbook, as well as with the presentations he heard at early meetings. This changed when he met Ross Ashby in 1967, and changed even further in 1968, when Bertalanffy joined him in Buffalo.

He further explained that he had been uncomfortable with the idea of a "systems movement" until he met Bertalanffy. In Bertalanffy he found a deep love of both science and humanity. (The early days of the SGSR involved many discussions about "science in the service of humanity.") Bertalanffy saw GST as a new way of thinking which could offer new hope.

Rosen met George Klir in 1974. Klir was a professor in Binghamton, NY, in whom Rosen found a kindred spirit. Both considered mathematics to be essential to the understanding of systems. Klir even convinced Rosen to take the role of president of the SGSR in 1981.

By 1982, Kauffman began another shift from the applied to the theoretical. He began working again on his theories and calculations and was able to create a proof for the phase transition that he could only guess about in 1971. If the chemicals and interactions in a system were too simple, nothing would happen. The system would remain “subcritical.” If the system reached enough complexity, it would become “supercritical” and autocatalysis became inevitable.

Also in 1982, Kauffman met Doyle Farmer, a physicist at Los Alamos. Farmer invited Kauffman to begin visiting the lab and introduced him to Norman Packard, a computer scientist at the University of Illinois. By 1985, the three had begun a close collaboration and in 1986 Kauffman had bought a house in Santa Fe and was splitting time between there and the University of Pennsylvania.

It should be noted in passing that the University of Pennsylvania, like the University of Chicago, and MIT, and several other institutions, was a place of conversion in systems and cybernetic history. Kauffman was there from 1975 to 1995. Overlapping with much of that time was Russ Ackoff, a key figure in systems science, as a professor in the Wharton School from 1964 until 1986, and then emeritus until his death in 2009. Ackoff’s emphasis shifted from operations research to formal work in systems with the creation of The Social Systems Science program. This coincided with two of Ackoff’s more noted publications, *On Purposeful Systems*, written with Fred Emery in 1972, and *Redesigning the Future: A Systems Approach to Societal Problems* published in 1974. The “S-cubed” program, as it came to be known, included many other noted systems scientists as faculty at different points, including C. West Churchman, Eric Trist, Fred Emery, and Hasan Ozbekhan.

Despite the location, Ackoff and Kauffman never knew each other. The distance between the department of biology and the business school was apparently much greater than any geographical separation, as is common in most universities.

Moving Forward

The work that began as cybernetics, systems science, and complexity science continues on in various forms. The American Society for Cybernetics and the International Society for the Systems Sciences (ISSS) continue to hold annual meetings. The ISSS signed a memorandum of understanding with the International Society of Systems Engineers (INCOSE) in 2010, launching a number of joint projects, and the ISSS reaffiliated with the American Association for the Advancement of Science in 2018. According to research done by Umpleby et al. (2017), the number of books related to cybernetics has grown rapidly since 2000, particularly in Europe and North America.

The International Federation for Systems Research was founded in 1980. The federation began as a collaboration of three organizations: the Österreichische Studiengesellschaft für Kybernetik (OSCG), the Systemgroup Nederland, and the Society for General System Research (now the ISSS). It developed into a federation of 45 member organizations, interested in systems and cybernetics, around the world.

The Santa Fe Institute continues to operate and to be engaged in research, as well as hosting summer schools to teach complexity science. In addition, there are the Konrad Lorenz Institute for Evolution and Cognition Research and the International Institute for Applied Systems Analysis (IIASA) in Vienna. The University of Amsterdam and

Nanyang Technological University in Singapore host programs, as does the New England Complex Systems Institute in Boston, Massachusetts, in the USA.

Complexity science was applied in the private sector, through the work of the BiosGroup, a company founded by Kauffman with the consulting firm Ernst & Young in 1997. Its clients included Southwest Airlines, P&G, Ford, Boeing, SAP AG and Texas Instruments, as well as government agencies like the Office of Naval Research and the Internal Revenue Service. In 2000, it received investments of $5 million from Procter & Gamble and $8 million from Ford Motor Company. At its peak, BiosGroup employed about 150 people in offices in Santa Fe, Boston, London, Bulgaria, and Washington, DC. It is being acquired by another company this year.

Systemic theories have also found their ways into applied research, primarily through systems biology in centers such as the Institute for Systems Biology in Seattle, Washington. Researchers like Sui Huang and Ilya Schmulevich have continued to work with Kauffman, developing ideas that he proposed decades earlier. For example, from an article by Huang et al. (2009):

> We present here the idea of "cancer attractors", which was first suggested by Stuart Kauffman 40 years ago as a corollary of an encompassing theory from complex systems studies that has only recently begun to find experimental support thanks to genomic technologies (p. 2)

These examples are significant because they illustrate what may be a common path from theoretical to experimental or applied research. Kauffman obtained consistent funding for traditional biological research (through the National Science Foundation, National Institutes of Health, and the American Cancer Society) from 1969 through 2005. His theoretical work, however, has only recently been adopted into applied in ways which are helping to broaden research beyond molecular biology.

Kauffman's own work continues with forthcoming books and papers. Building on the work of Kauffman and Brian Arthur, Thurner et al. (2018) have published an excellent primer of theories related to complex systems, targeted to graduate students in physics and mathematics. Researchers such as Karl Friston, at University College London, appear to be revisiting complexity in neurological systems.

Significant challenges remain with respect to the theoretical and philosophical perspectives currently dominating fields like artificial intelligence and machine learning, which are simultaneously increasing complexity in our global systems, while attempting to capture and explain it. Though the roots of this work connect with the foundations of systems, cybernetics, and complexity (e.g., von Neumann and others), there has been little recent collaboration between these domains.

Conclusions

This chapter has attempted to capture some of the collective histories and connections between the domains of systems, cybernetics, and complexity. Given the limitations of a single chapter, it is inherently incomplete. If successful, it has created a context into which other chapters in this book can be situated.

Systems, cybernetics, and complexity have been interpreted by some as extensions (or attempts to extend) science. Others have seen them as grandiose ideas lacking scientific foundations. Still others have taken them as affronts or challenges to science – involving taboo notions such as purpose or holism.

Systems, cybernetics, and complexity have each added in different ways to the more traditional disciplines of science. At the same time, they have also challenged existing tenants. They have built upon science while also moving towards the paradigm shifts described by Kuhn. Many of the foundational ideas proposed decades ago are only recently being rediscovered and or revisited. In many ways, they represent long trajectories of thinking rather than short-term findings.

Traditional science has 100 years of certainty about quantum mechanics, but apparently no way yet to reconcile that with classical physics. We know that there is order in the universe, but it is not an absolute order determined by the properties of atomic particles.

Many of the questions raised in systems, cybernetics, and complexity continue to be relevant today, and for advancing science into the future. Ancient Greeks believed that mathematics represented the order of the universe. Mathematics is the basis for computer technology, which has become the primary tool of science, as well as of human technologies in this age. Mathematics is certainly the "language" of physics and chemistry. Rosen believed that it was the key to biology – if math itself could evolve to the necessary levels of complexity. Biology, however, has not historically been a mathematical science. Is math the key to all science, and if so, in what form?

Both the dreams and fears of cybernetic technologies continue to expand in the world today. For some, digital technologies will be the answer for world problems, and the future beyond human frailties. Our future "selves" or identities may be incorporated into cyber-realities. Ultimately, biological species may give way to digital ones. For many people, such a future is the ultimate nightmare. If humans continued to exist, it might only be as pets or slaves.

In a world moving towards technological perfection, do ethics or morality have a place? Are those only aspects of human weakness or do they matter in some larger way? Science long ago separated itself from purpose and meaning, but humanity did not. One path forward would be that science expands to revisit phenomenon far beyond material causality. Another would be that science becomes only one aspect of human investigation and knowledge.

Complexity looms large in our problems and our potentials. The world is not one of all-equal connections. As Kauffman has explained, the universe of possibilities is too vast for every conceivable combination or connection to have occurred. In fact, as described by C. S. Peirce, the universe appears to "take habits." Order is free (i.e., spontaneous) and it exists within realms of probabilities.

Newton created classical physics and used it to describe a universe of pure order. Laplace took that universe and made it deterministic and predictable. If you knew the position and momentum of every particle in the universe, you could know all the past and all of the future. The believers in supercomputers and "big data" may have similar dreams.

According to Kauffman, we live poised at the edge of chaos, in a space between the rigidly determined and the purely random. It is the necessary space in which the novelty of nature brought forth our biosphere, and life. That does not mean that it is unique. Similar novelty may exist on many other planets. It is a novelty, though, in which the Logos of order needs the creativity of Eros, in delicate balance with each other.

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