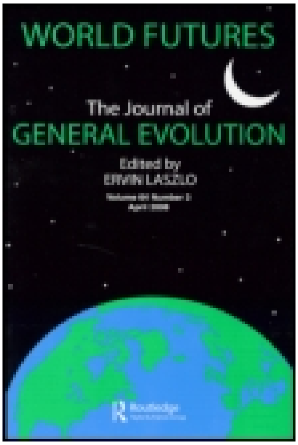

World Futures: The Journal of Global Education

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gwof20

The Genesis of Complexity

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Available online: 14 Jul 2011

World Futures, 67: 380–394, 2011

ISSN: 0260-4027 print / 1556-1844 online
DOI: 10.1080/02604027.2011.585915

THE GENESIS OF COMPLEXITY

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The theories of complexity comprise a system of great breadth. But what is included under this umbrella? Here we attempt a portrait of complexity theory, seen through the lens of complexity theory itself. That is, we portray the subject as an evolving complex dynamical system, or social network, with bifurcations, emergent properties, and so on. This is a capsule history covering the twentieth century. Extensive background data may be seen at www.visual-chaos.org/complexity.

KEYWORDS: Complex dynamical systems, cybernetics, system dynamics.

INTRODUCTION: THE THREE ROOTS

This analysis of the history of complexity theory during the twentieth century will describe its three roots, and their interactions and bifurcations as a complex dynamical system. These roots are cybernetics, general systems theory (theoretical biology), and system dynamics. I begin by telling their separate stories, then describe their links, their fusion into the trunk of complexity, and end with capsule descriptions of the main branches of complexity theory today, and a personal memoir. I will use the scheme of Figure 1 for the cartography of complexity. Throughout, DST denotes Dynamical Systems Theory, a major branch of mathematics dating from Isaac Newton, which has pure, applied, and (more recently) computational aspects.

CYBERNETICS, 1946

Cybernetics is an interdisciplinary field born during World War 2 on the East Coast of the United States. Its story is well told in Steve Heims's history, *The cybernetic group*, of 1991. It is placed on Figure 2.

The Cybernetic Group

The "cybernetic group" is Heims's name for a group of eight "cyberneticians" from three fields:

This article is dedicated to Heinz Pagels.

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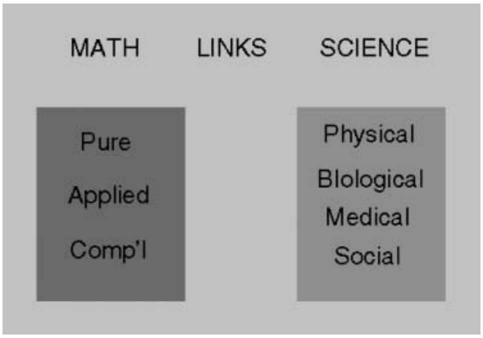

Figure 1. A two-dimensional state space for the branches of complexity. For MATH you may read DST, as that is the only branch of math involved here.

- Mathematics: Norbert Wiener, John von Neumann, Walter Pitts
- Engineering: Julian Bigelow, Claude Shannon
- Neurobiology: Rafael Lorente de No, Arturo Rosenblueth, Warren McCulloch

In 1942, they met in New York on the instigation of the Josiah Macy Foundation: McCulloch and Pitts from the University of Illinois, Chicago; Von Neumann from the Institute of Advanced Studies, Princeton; Wiener, Bigelow, Rosenblueth, and Shannon from MIT, Cambridge, and Lorente de No from the Rockefeller Institute, New York. In 1943, McCulloch and Pitts published their very seminal paper on neural networks. In 1946, the group increased to 21 members.

The Macy Conferences

Cybernetics itself emerged from a series of ten meetings organized again by the Macy Foundation from 1946 to 1953, in which the cyberneticians were joined

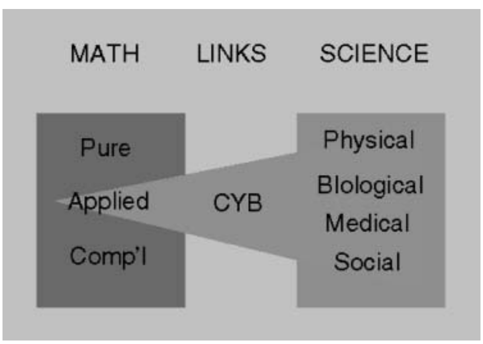

Figure 2. Cybernetics (CYB) placed on the map of complexity. The classic McCulloch and Pitts paper of 1943 connected applied DST, physics, and neurophysiology. The Macy Conference of 1946 expanded the domain into the social sciences.

with a group of social scientists led by anthropologists Gregory Bateson and Margaret Mead, and including Gestalt social psychologist Kurt Lewin. These Macy Conferences comprised vociferous discussions, each triggered by a brief statement by one of the group. The first wave of cybernetics may be taken to mean the sum of all these discussions. Later of course, its meaning was refined by various people, but the transcripts of the first nine meetings have been published, and summarized by Heims in his book, so you may derive your own definition of cybernetics if you like (Foerster 1952). Certainly circular and reticular causality, feedback networks, artificial intelligence, and communication are among its main themes.

GENERAL SYSTEMS THEORY, 1950

General systems theory, the brainchild of Ludwig von Bertalanffy in Vienna, evolving since the 1920s, may be regarded as a European counterpart to the American cybernetics movement. See Figure 3.

Von Bertalanffy

Homeschooled in biology, Von Bertalanffy attended meetings of the Vienna Circle—a group of scientists and philosophers devoted to logical positivism organized by Morris Schlick, professor of Philosophy at the University of Vienna. Although opposed to the positivist philosophy of science, Von Bertalanffy earned a Ph.D. with Schlick, and became professor of biology at the University of Vienna. His first books were devoted to theoretical biology (1928, 1932). Around the time of Von Bertalanffy's immigration to North America in 1950, his ideas coalesced into GST, in which all systems were considered similar, whether physical, biological, or social. The main ideas of GST were holism, organicism, and open systems, as found in the biological sphere, but Von Bertalanffy generalized grandly to social systems, and world cultural history. On arriving in North America after 1950,

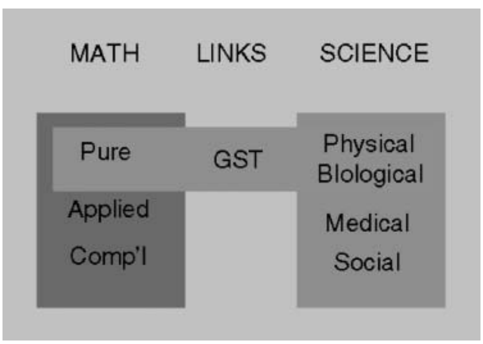

Figure 3. General Systems Theory (GST) on the map. We may take 1950, the birthdate of GST, or perhaps 1956, the birthdate of the SGSR, as the beginning of this link. Pure DST concepts were applied in GST to physical (or theoretical) biology.

Von Bertalanffy moved about widely, visiting Stanford in 1954. At Stanford, with Ralph Gerard, Kenneth Boulding, and Anatol Rapoport, Von Bertalanffy created the Society for General Systems Research (SGSR) in 1956 (Davidson 1983).

Waddington

The Theoretical Biology Club at Cambridge University in England was organized by Conrad Hal Waddington in the 1930s. Joseph Henry Woodger, a member of the club, translated Von Bertalanffy's first book from German to English, establishing a connection between Vienna and Cambridge. On leaving Vienna for good in 1948, Von Bertalanffy stopped briefly in England, on the invitation of Woodger. A series of meetings on theoretical biology, somewhat like the Macy Conferences on cybernetics, were organized by Waddington under the auspices of the International Union of Biological Societies (IUBS). Taking place in the Villa Serbelloni on Lake Como in the north of Italy in the years 1966–1970, they were attended by engineers, biologists, mathematicians, and others, primarily from Europe. These meetings, and their published proceedings edited by Waddington, projected GST into a very wide interdisciplinary world of its own in the 1970s (Waddington 1968–1972).

SYSTEM DYNAMICS, 1956

Dynamical systems theory is a large branch of mathematics created by Isaac Newton, and given its modern form by Poincare around 1880 (see Figure 4).

Aspects of DST

Its pure aspect came to be known as chaos theory after 1975 or so, following the dramatic impact of the computer revolution, and the consequent discovery of chaotic attractors (Abraham 2000). Catastrophe theory and fractal geometry are related subjects. The applied aspect of DST traditionally embraced much of mathematical physics, biology, medicine, and the social sciences. Since the advent

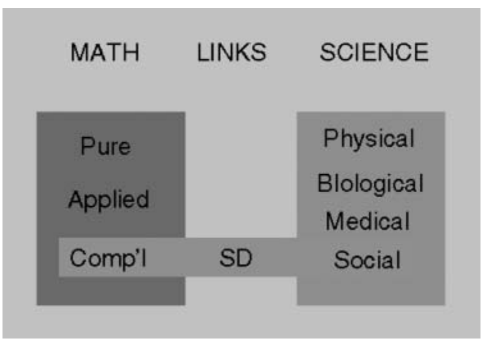

Figure 4. System Dynamics (SD) on the map. Computational DST was applied by Forrester, beginning in 1956, to industries, regarded as complex dynamical systems.

of analog and digital computers in the twentieth century, the applications have expanded greatly in scope and importance. One of the threads of computational and applied DST is crucial to the evolution of the theories of complexity: system dynamics (SD). This thread, primarily the work of Jay Forrester and his group at MIT, is the goal in this section (Forrester 1961).

Early Analog Machines

Mechanical analog computers go back to James Clerk Maxwell (1855) and James Thompson (1822–1892, brother of Lord Kelvin) in the 1860s (Goldstine 1972, 40). Important developments by Vannevar Bush at MIT, beginning in 1925, resulted in large machines such as the Differential Analyzer, capable of integrating large-scale dynamical systems (Zachary 1997, 48). Eventually these were used as weapons during World War 2 (Goldstine 1972, 84; Williams 1997, 201). Bush—who was working jointly with Wiener by 1929—was an extraordinary genius, and foresaw hypertext and the Internet (Burke 1994).

Early Digital Machines

The first digital computer is attributed to John Atanasoff, at Iowa State College, in 1942 (Burks and Burks 1988). The further development of digital computers and computational math was the work of mathematicians and electrical engineers during World War 2, especially we may note Norbert Wiener at MIT, John von Neumann, and Julian Bigelow at Princeton, and Alan Turing in England, who will figure prominently in the story.

System Dynamics

Just as Vannevar Bush was finishing his mechanical analog computer, in 1940, Jay Forrester founded the Servomechanism Laboratory of MIT, and began working on digital computers. He founded the MIT Digital Computer laboratory in 1951, and is credited with crucial inventions, including the magnetic core memory device (Goldstine 1972, 212). In 1956, toward the end of the career of Vannevar Bush, Forrester carried on the MIT tradition of computational applied dynamics, but using digital computers and modern software for simulation and graphical display of complex dynamical systems (Wolstenholme 1990, Foreword by Forrester). His first book on this work, *Industrial dynamics* of 1961, broke new ground. Eventually this technique became known as system dynamics, and his System Dynamics Group grew from 1968 into the present day Sloane School of Management of MIT.

LINKS BETWEEN ROOTS, 1956–1970

Between the three roots there developed many links, which we consider briefly here, pairwise and chronologically.

CYB/GST, 1956

The Macy conferences in New York (1946–1953) immediately preceded the founding of the SGSR in Palo Alto in 1956. Ralph Gerard, a neurophysiologist member of the Macy meetings, was among the four founders of GSRS. So although theoretical biology had a long history in Europe (Lotka from 1907, von Bertalanffy from 1928, Waddington in the 1930s), the GST movement, as it formed in 1956, was aware of CYB from the beginning.

CYB/GST, 1966

The Macy Conferences preceded the Serbelloni meetings (1966–1970) by some 20 years, and as far as we know no member or guest of the Macy events attended any of the IUBS gatherings. Yet three key books on cybernetics had been published in between (Wiener 1948; Ashby 1956; Pask 1961) and one may assume that the GST people at Serbelloni were aware of them. Further, Arthur Iberall—the physicist, founder of homeokinetics, and co-worker with McCulloch at MIT—attended the second Serbelloni meeting in 1967.

CYB/SD, 1956

First of all, the cyberneticians included three mathematicians, who would have been slightly acquainted with DST. Yet none of them were specialists of DST. The proximity of Wiener and Forrester, both working at MIT, would be the main link from CYB to SD and vice versa. This link extended the earlier (from 1927) working relationship of Wiener and Vannevar Bush. Further, references in Forrester's books reveal the influence of cybernetician/social psychologist Kurt Lewin (Forrester 1969, 14).

GST/SD, 1970

The Club of Rome was convened by Aurelio Peccei in Rome in April 1968. This group was aware of GST. In June 1970, now numbering 75 members, the Club met in Bern and focused on the problem of the predicament of humankind. Jay Forrester of the System Dynamics Group at MIT attended this meeting, and persuaded the members to come to MIT to see the capability of his modeling and simulation technology for forecasting the limits of the biosphere. This resulted in the World Dynamics model of the SD Group, and the Limits to Growth project, which predicted that the Earth would be overloaded within a century. This project established system dynamics (complex dynamical systems theory) as the mathematical form of GST (Meadows 1972).

COMPLEXITY, THE TRUNK, 1977

Cybernetics had its fluorescence, then general systems theory, and system dynamics, as we have seen. The links among the support communities of these interdisciplinary zones rapidly grew in number and strength. Eventually, the whole complex system of ideas became one larger system, for which we may use the theories of complexity as a nickname.

The complexity concept emerged early on, perhaps as early as 1925 in Lotka's classic, *Elements of physical biology*. It may be seen here and there in the literature of CYB, GST, and SD. But perhaps the first text devoted entirely to the subject (and arguably still the best) is Waddington's *Tools for thought*, of 1977. Since then, there are many books devoted to complexity. Among these, we may mention especially:

- 1969, Herbert Simon, *The sciences of the artificial*
- 1969, Jay Forrester, *Urban dynamics*
- 1988, Heinz Pagels, *The dreams of reason*: *The computer and the rise of the sciences of complexity*
- 1989, Gregoire Nicolis and Ilya Prigogine, *Exploring complexity, an introduction*

Others are listed in the bibliography.

THE BRANCHES OF COMPLEXITY, 1990

By 1990 or so, more than a score of distinct areas could be identified as branches of complexity theory, along with CYB, GST, and SD (Figures 5, 6, and 7). Active branches of computational mathematics derived from the three roots of complexity, with approximate creation dates, include:

- ANNs, SD, 1943
- Cellular automata (CAs), 1950
- Cellular dynamical systems (CDs), morphogenesis, self-organization, 1952
- Catastrophe theory, bifurcation theory, 1967
- Chaos theory, 1974, Fractal geometry, 1975

Active branches of the sciences derived from the roots of complexity include:

- Schismogenesis and netwar, 1920
- Mathematical and theoretical biology, 1925
- Biospherics, 1944
- Ecology, 1964, Homeokinetics, 1967
- Synergetics, 1975
- Autopoesis, General evolution theory, 1985
- Gaia theory, 1988

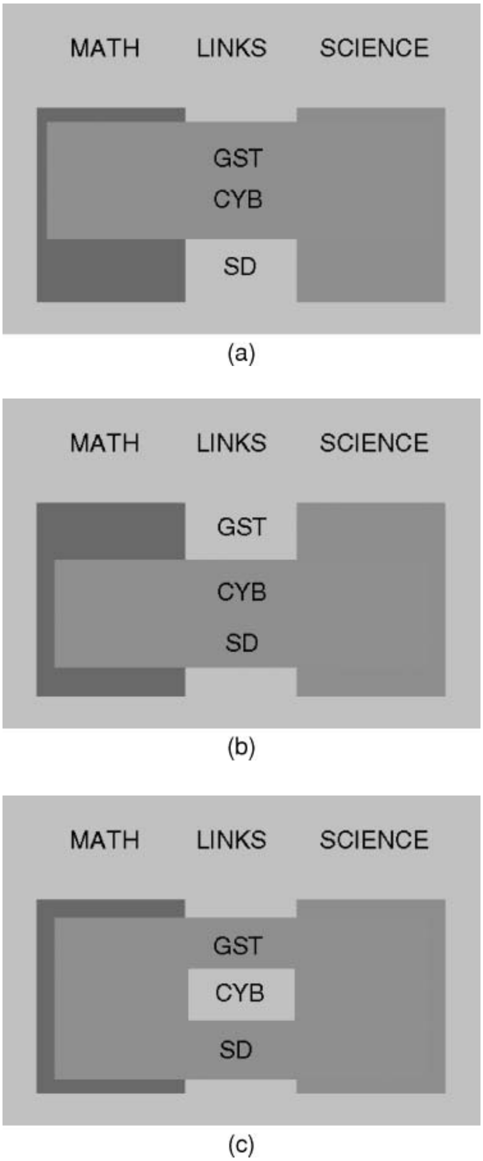

Figure 5. (a) Links CYB/GST, 1956. As soon as the SGSR got underway in 1956, these two communities were connected. In fact, Ralph Gerard, one of the four founders of the SGSR, had been a member of the Macy meetings. (b) Links CYB/SD, 1957. When Jay Forrester arrived at MIT, he fell into a well-established hotbed of cybernetics. This must have been a factor in his founding of SD at MIT in 1956. (c) Links GST/SD, 1970. The pioneer connecting event here is the attendance by Forrester at a meeting of the Club of Rome in 1970, leading up to the Limits to Growth modeling project.

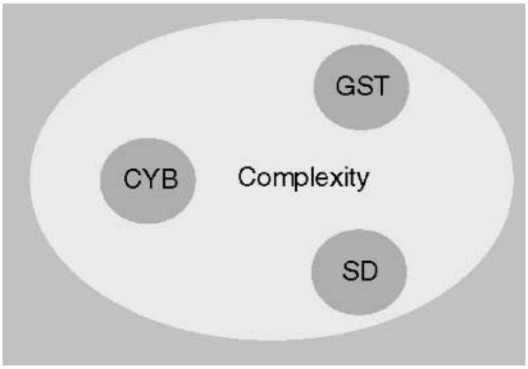

Figure 6. The trunk of complexity. Here, the central (link) zone is widened.

THE WHOLE TREE, 1940–1990

We may now put all this date-stamped history together into a bifurcation diagram. Figure 8 shows five cross-sections of the whole tree, complete with tree rings.

PERSONAL HISTORY, 1960–2000

From 1960 through 1968, DST was one of my primary areas of research in pure mathematics. Upon contacting new experimental results from analog and digital computer research, this line of work came to a crisis, as I have recounted elsewhere (Abraham 2000; ch. 6). By 1971 many of us had turned to the sciences for fresh inspiration, and a new research program for DST. I was intrigued by the field theories of Kurt Lewin and Wilhelm Reich. In 1972, Rene Thom (recently returned from the Serbelloni meetings) introduced me to the work of Hans Jenny, who had studied for years the patterns created in fluid media exposed to acoustic vibrations.

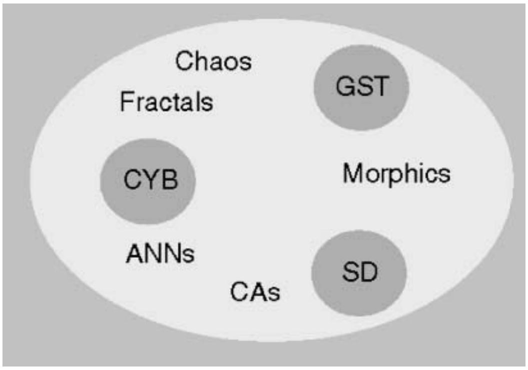

Figure 7. The branches of complexity. Here I show just a few of the more active math branches.

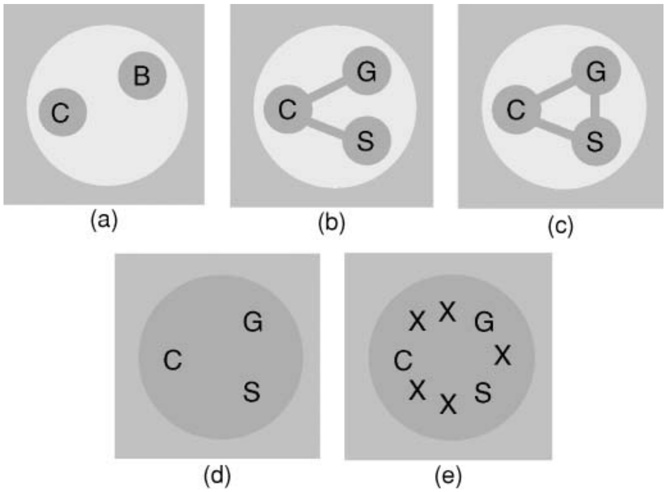

Figure 8. (a) The 1940s. CYB began in 1946. B denotes theoretical biology, the prehistoric root of GST, on the map since 1907. (b) The 1950s. GST emerges from B, and SD from the Bush tradition, in 1956. Both are linked with CYB from the start. (c) The 1960s. Toward the end of the 1960s, GST and SD link up, in preparation for the Club of Rome meeting in 1970. (d) The 1970s. Self awareness of the whole complexity complex gives birth to a new unified domain, evident in Waddington's book of 1977. (e) The 1980s. New branches become attached to the new domain in the 1980s, such as cellular automata (since 1950), chaos theory (branched from DST in 1975), and fractal geometry (since 1975).

By 1974 I had constructed a laboratory inspired by Jenny to continue his work. My interest was to discover the "edge of chaos" in vibrating fluid experiments.

At this time, my friend Terence McKenna introduced me to Erich Jantsch. Erich was, at that time, a professor of management science at UC Berkeley, impressed by Prigogine's work on self-organization, and was editing a volume with Conrad Waddington (the theoretical biologist) called *Evolution and consciousness* (published in 1976). I recognized Erich, although quiet and modest, as an original polymath and genius. He had just completed a book, *Design for evolution* (1975), which was a seminal work on general evolution theory (GET). He invited me to contribute a chapter to his book with Waddington, and in the summer of 1974 I sent him a report on my vibrations project. Waddington died during the preparation of this book. When the book was published, I found myself in the company of Waddington, Prigogine, Jantsch, and other luminaries of GST, GET, and so on. I read their works for the first time.

Soon, Erich invited me to contribute to another collection, *The evolutionary vision*. This time I sent him an essay more in the line of his main interest, the evolution of consciousness. And when this book appeared in 1981, I found myself again in interesting company: Prigogine, Jantsch, Kenneth Boulding, Hermann

Haken, Peter Allen, Howard Pattee, Elise Boulding, and several others, visionaries of self-organization, GST, GET, and so on. Eventually I met most of them. Unfortunately, Erich died prematurely before this book appeared.

My brother Fred, in the early 1970s, had created a frontier laboratory of neurophysiology at the Brain Research Institute, UCLA. Partly through his influence, I developed an interest in brain waves, and all this led to my meeting Gene Yates and Arthur Iberall (who had been at Serbelloni in 1967) in a panel organized by Walter Freeman, the brain chaos pioneer, at the Winter Conference on Brain Research (WCBR), a brain child of my brother Fred, in January 1979. This in turn led to my invitation to Yates's conference on self-organizing systems in Dubrovnik, August 1979. Seen as a successor to cybernetics and GST, this meeting brought together veterans of the Serbelloni conferences of the preceding decade—Michael Arbib, Brian Goodwin, Arthur Iberall, Howard Pattee—with like-minded experts of many sciences (Yates et al. 1987).

In May 1985, a call from David Loye and Riane Eisler led to a meeting with Ervin Laszlo, who had studied with Von Bertalanffy, and became a leading systems philosopher. This meeting was part of their program to create the General Evolution Research Group (GERG), which even today carries on the unification program of Cybernetics, GST, GET, Theoretical Biology, Self-Organization, Complexity, and so on.

My great luck in meeting these extraordinary thinkers has had a powerful effect on my mathematical work, and I continue my experimental program on complex and cellular dynamical systems with digital computers and computer graphics in the shadow of their influence.

CONCLUSION, THE FUTURE

We may surmise that the complex system of complexity theories is at an early stage in its own evolution. Despite long efforts by brilliant people, little actual theory has been established so far. One would hope that evolution would race on, bringing our species to a new level of intelligence. Unfortunately, the future is not so clear. So far, universities have not supported complexity, and research and publication activities are thinning out. (For the latest, consult the online *Complexity Digest*, at www.comdig.org.) Nevertheless, GST has grown into an enormous community, represented by the International Society of Systems Science (ISSS), CYB continues its very nonlinear evolution, in a second wave (since 1865) and a third (since 1985) as for example in the American Society for Cybernetics (ASC) and similar groups in other nations, and SD lives on at MIT, in the journal *System Dynamics Review*, and in the children of its original SD software, DYNAMO, such as STELLA, Berkeley Madonna, and others. Also, GST has emitted a new major branch, General Evolution Theory, with its General Evolution Research Group (GERG), and its journal, *World Futures*. The future is not ours to see, and the theories of complexity may yet thrive, or starve. Time will tell.

GLOSSARY

Artificial neural network (ANN)—Complex dynamical system in which the nodes are analogs of biological neurons, and the connections are arranged so that the whole system performs as an analog of a biological nervous system.

Attractor—Dynamical equilibrium of a DS; **a**ttracts all nearby points**; t**hree types: static (point), periodic (cyclic), chaotic.

Autopoesis—Second wave of cybernetics**; d**ue to Maturana, who had worked with McCulloch, and Varela.

Basin of attraction—Most important attribute of an attractor of a DS; **s**et of initial points tending to the same attractor.

Bifurcation—Change in the attractor/basin portrait of a dynamical scheme; **c**haracterized by a loss of stability**; t**hree types: subtle, explosive, and catastrophic.

Biospherics—aka biogeochemistry; **f**ounded by V. I. Vernadsky.

Catastrophe theory—Branch of math created by Rene Thom ca 1966**; s**tudy of catastrophic bifurcations of a dynamical scheme.

Cellular automaton (CA)—Type of math model created by Stan Ulam in 1950**; d**eveloped extensively by von Neumann ca 1952; **a** lattice of identical finite state machines interconnected by a rule, the same at each node**; e**xample: Conway's Game of Life.

Cellular dynamaton (CD)—Cellular dynamical system, or lattice dynamical system; **t**ype of math model due to Rashevsky ca 1930; **d**iscrete model for partial differential equations of evolution type.

Chaos theory—Synonym for dynamical systems theory; **c**omplex dynamical systems theory.

Complex dynamical system—A network of simple dynamical systems.

Complexity—Measure of complexity of a dynamical system or one of its attractors.

Complexity theory—Study of complex dynamical systems; **e**specially, schemes of cellular dynamical systems.

Cybernetics (CYB)—Field created by Norbert Wiener ca 1942; **d**iffused by the Macy Conference, 1946; Wiener's book published 1948.

Dynamical scheme—Family of DS depending on control parameters.

Dynamical system (DS)—Two types: continuous, discrete.

Dynamical system, continuous—Autonomous system of ordinary differential equations.

Dynamical system, discrete—Iterated map system, iterated function system.

Dynamical systems theory (DST)—Branch of math founded by Poincare ca 1882; early roots in Lord Rayleigh's work on musical instruments; **q**ualitative (or geometric) theory of dynamical systems.

Ecology—Founded by G. Evelyn Hutchinson; **s**tudy of ecosystems.

Emergence—Roughly equivalent to self-organization; study of emergence of order in a field of chaos; appearance of a property or simplicity in a CDS scheme; study of bifurcations in a cellular dynamical scheme; related to morphogenesis.

General Evolution Theory (GET)—Offshoot of GST and SD due to Ervin Laszlo ca 1985**; d**eveloped by the General Evolution Research Group, GERG.

General Systems Theory (GST)—Field created by von Bertalanffy ca 1950; **s**tudy of properties shared by all complex systems.

Gestalt theory—Holistic branch of psychology due to Wertheimer, Kohler; Berlin ca 1930, Smith College ca 1942**; a**pplied to social theory by Kurt Lewin, founder of social psych.

Homeokinetics—Field founded by Arthur Iberall ca 1950; **g**eneral theory of evolution in physical, biological, and social systems.

Homeorhesis—Term introduced by C. H. Waddington ca 1957; **d**ynamic equilibrium of a natural system**; n**onstatic attractor of a DS.

Homeostasis—Term introduced by W. B. Cannon ca 1932 or perhaps Claude Bernard ca 1850; **s**table equilibrium of a natural system**; s**ame as static (point) attractor in DST.

Morphogenesis—Branch of math founded by Alan Turing ca 1952 with ancient and classical roots, for example, Kepler, Goethe.

Politicometrics—Application of DST to wars and arms races; **c**reated by Lewis Frye Richardson ca 1920.

Self-organization—Synonym for emergence.

Synergetics—Another interdisciplinary science paradigm; **f**ounded by Buckminster Fuller; **f**urthered by Herman Haken.

System dynamics (SD)—Applied version of DST; **f**ounded by Jay Forrester ca 1950; **a**pplied to the world system in the Limits to Growth study sponsored by the Club of Rome.

Theoretical biology—Mythical field similar to theoretical physics; **s**earch for laws applying to all biological systems**;** Waddington's Serbelloni conferences, 1966, 1967, 1968, 1970.

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