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COLLECTED VIEWS ON COMPLEXITY IN
SYSTEMS

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The term complexity is used in many different ways in the systems domain. The different uses of this term may depend upon the kind of system being characterized, or perhaps the disciplinary perspective being brought to bear.

The purpose of this paper is to gather and organize different views of complexity, as espoused by different authors. The purpose of the paper is not to make judgments among various complexity definitions, but rather to draw together the richness of various intellectual perspectives about this concept, in order to understand better how complexity relates to the concept of engineering systems.

I have either quoted directly or done my best to properly paraphrase these ideas, apologizing for when I have done so incorrectly or in a misleading fashion. I hope that this paper will be useful as we begin to think through the field of engineering systems.

The paper concludes with some short takes -- pungent observations on complexity by various scholars -- and some overarching questions for subsequent discussion.

AUTHOR

SOURCE

A THEORY OF COMPLEX SYSTEMS

Edward O. Wilson	<i>Consilience: The Unity of Knowledge</i>
Herbert Simon	The Architecture of Complexity, Proceedings of the American Philosophical Society, Vol. 106, No. 6, December 1962
Kenneth Boulding	as cited in Daniel Katz and Robert Louis Kahn, <i>The Social Psychology of Organizations</i>

DEFINITIONS OF COMPLEXITY

Joel Moses	Complexity and Flexibility (working paper)
Eberhardt Rechtin and Mark Maier	<i>The Art of System Architecting</i>
Peter Senge	<i>The Fifth Discipline: The Art and Practice of the Learning Organization</i>
Robert L. Flood and Ewart R. Carson	<i>Dealing with Complexity: An Introduction to the Theory and Application of Systems Science</i> , citing Vemuri in <i>Modeling of Complex Systems: An Introduction</i>
Peter Coveney and Roger Highfield	<i>Frontiers of Complexity: The Search for Order in a Chaotic World</i>
John Sterman	<i>Business Dynamics: Systems Thinking and Modeling for a Complex World</i>
Charles Perrow	<i>Normal Accidents: Living with High-Risk Technologies</i>
Joseph Sussman	<i>Introduction to Transportation Systems</i>

SOCIAL/TECHNICAL SYSTEMS

J. Morley English (ed.)	<i>Economics of Engineering and Social Systems</i>
Thomas P. Hughes	<i>Rescuing Prometheus</i>
Paul Ormerod	<i>Butterfly Economics: A New General Theory of Social and Economic Behavior</i>

BUSINESS/ORGANIZATIONS/POLICY

- _____ Complex Equations, *The Economist* June 5, 1999.
- Daniel Katz and Robert Louis Kahn *The Social Psychology of Organizations*
- A. O. Hirschman and C. E. Lindblom Economic Development, Research and Development, Policy Making: Some Converging Views, *Behavioral Science*, vol. 7 (1962), pp. 211-22.
- David Levy Applications and Limitations of Complexity Theory in Organizational Theory and Strategy, *Handbook of Strategic Management*.

COMPLEX ADAPTIVE SYSTEMS/SELF-ORGANIZATION

- John H. Holland *Hidden Order: How Adaptation Builds Complexity*
- W. Brian Arthur On the Evolution of Complexity -- in *Complexity: Metaphors, Models, and Reality*, G. A. Cowan, David Pines and David Meltzer (eds.)
- Stuart Kauffman *At Home in the Universe: The Search for the Laws of Self-Organization and Complexity*

COMPLEXITY: SOME SHORT TAKES

SOME OVERARCHING QUESTIONS

REFERENCES

A THEORY OF COMPLEX SYSTEMS

1. From *Consilience: The Unity of Knowledge* by **Edward O. Wilson**:

The theme of this book, consilience, refers to the web of interconnection among disciplines -- the ultimate tying together of all knowledge.

Wilson discusses complexity theory, saying that The greatest challenge today, not just in cell biology but in all of science is the accurate and complete description of complex systems. Scientists have broken down many kinds of systems. They think they know the elements and the forces. The next task is to reassemble them, at least in mathematical models that capture the key properties of the entire ensembles. Success in this enterprise will be measured by the power researchers acquire to predict emergent phenomena when passing from general to more specific levels of organization. That in simplest terms is the great challenge of scientific holism.

Wilson notes that the physicists have done this. By treating individual particles such as nitrogen atoms as random agents, they have deduced the patterns that emerge when the particles act together in large assemblages, but he says the subject matter of physics is the simplest in science. It will be much harder in biology, he suggests.

He defines complexity theory as the search for algorithms used in nature that display common features across many levels of organization. He says complexity theories, At their best, they might lead to deep new laws that account for the emergence of such phenomena as cells, ecosystems, and minds.

He is not convinced about the approach, but is hopeful. He says that some of the elementary concepts like chaos and fractal geometry have been useful in modeling the physical world. To be successful in his field of biology, what complexity theory needs is more empirical information and some day, perhaps, we will have a true theory of biology.

Wilson also discusses the opportunity of economists to build on biology and psychology. He refers to going from the micro to the macro: The ensemble of processes by which the mass of individual decisions are translated into social patterns. I think this bottom-up idea will be terribly difficult to realize, but it is consistent with Wilson's theme of consilience.

2. From **Herbert Simon's The Architecture of Complexity**, Proceedings of the American Philosophical Society, Vol. 106, No. 6, December 1962:

A number of proposals have been advanced in recent years for the development of general systems theory which, abstracting from properties peculiar to physical, biological, or social systems, would be applicable to all of them. We might well feel that, while the goal is laudable, systems of such diverse kinds could hardly be expected to have any nontrivial properties in common. Metaphor and analogy can be helpful, or they can be misleading.

All depends on whether the similarities the metaphor captures are significant or superficial.

It may not be entirely vain, however, to search for common properties among diverse kinds of complex systems. The ideas that go by the name of cybernetics constitute, if not a theory, at least a point of view that has been proving fruitful over a wide range of applications. It has been useful to look at the behavior of adaptive systems in terms of the concepts of feedback and homeostasis and to analyze adaptiveness in terms of the theory of selective information. The ideas of feedback and information provide a frame of reference for viewing a wide range of situations, just as do the ideas of evolution, of relativism, of axiomatic method, and of operationalism.

3. **Kenneth Boulding**, as cited in Daniel Katz and Robert Louis Kahn, *The Social Psychology of Organizations*, describes a hierarchy of systems representing eight levels of complexity.

- Frameworks of static structures
- The clockworks of physics and astronomy
- The control mechanism of cybernetic system
- The cell or self-maintaining structure
- The genetic or plant level
- The animal level with purposive behavior and self-awareness
- The human level
- Social organization or individuals in roles

DEFINITIONS OF COMPLEXITY

4. Complexity as per **Joel Moses** in his working paper **Complexity and Flexibility** :

There are many definitions of complexity. Some emphasize the complexity of the behavior of a system. We tend to emphasize the internal structure of a system. Thus our approach is closer to a dictionary definition of complicated. A system is complicated when it is composed of many parts interconnected in intricate ways. Let us ignore the near circularity of the definition. The definition points out two features of the concept. It has to do with interconnections between parts of a system, and it has to do with the nature of these interconnections (their intricateness). One can use information theory to get at the notion of intricateness in the sense that a highly intricate set of interconnections contains much information, whereas a highly regular one contains far less. For our purposes a simpler definition will be helpful. We shall define the complexity of a system simply as the number of interconnections between the parts.

Our view of complexity differs from that of the man on the street. Complexity is not an inherently bad property to us. Rather it is the coin of the realm in systems. You usually have to expend complexity dollars to achieve useful goals, such as increased functionality, efficiency or flexibility. The reason for the word usually above is that there are occasions when one can greatly simplify the design of a system and produce an equivalent one with many fewer parts and interconnections. We shall exclude such unusual situations. We shall be concerned with the more frequent situation where one wishes to modify an existing system in order to add functionality (e.g., more seats in an airplane, a new feature in Word), or increase efficiency. The ease with which such changes may be accomplished is related to the inherent flexibility of the initial design. Thus we are concerned with relationship between complexity and flexibility in a given system.

5. Complexity as per **Eberhardt Rechtin and Mark Maier** in *The Art of System Architecting*:

Complex: composed of a set of interconnected or interwoven parts.

System: a set of different elements so connected or related as to perform a unique function not performable by the elements alone.

It is generally agreed that increasing complexity is at the heart of the most difficult problems facing today's systems of architecting and engineering. Systems are simply growing in complexity -- the biggest cause of cost-overruns.

The authors argue that qualitatively different problem-solving techniques are required at higher levels of complexity than at low ones.

model (abstract) the system at as high a level as possible, then progressively reduce the

level of abstraction. In short, **Simplify**.

This primacy of complexity in system design helps explain why a single optimum seldom, if ever, exists for such systems. There are just too many variables.

6. Detail complexity vs. dynamic complexity as per **Peter Senge** in *The Fifth Discipline: The Art and Science of the Learning Organization*:

sophisticated tools of forecasting and business analysis usually fail to produce dramatic breakthroughs in managing a business. They are all designed to handle the sort of complexity in which there are many variables: detail complexity. But there are two types of complexity. The second type is dynamic complexity, situations where cause and effect are subtle, and where the effects over time of interventions are not obvious.

When the same action has dramatically different effects in the short run and the long (run), there is dynamic complexity. When an action has one set of consequences locally and a different set of consequences in another part of the system, there is dynamic complexity. When obvious interventions produce non-obvious consequences, there is dynamic complexity.

7. From *Dealing with Complexity: An Introduction to the Theory and Application of Systems Science*, by **Robert L. Flood and Ewart R. Carson**, citing **Vemuri** in *Modeling of Complex Systems: An Introduction*:

Complex situations are often partly or wholly unobservable, that is, measurement is noisy or unachievable (e.g., any attempt may destroy the integrity of the system).

It is difficult to establish laws from theory in complex situations as there are often not enough data, or the data are unreliable so that only probabilistic laws may be achievable.

Complex situations are often soft and incorporate values systems that are abundant, different and extremely difficult to observe or measure. They may at best be represented using nominal and interval scales.

Complex situations are open and thus evolve over time -- evolution may be understood to involve a changing internal structure, differential growth and environmentally caused adaptation.

8. From *Frontiers of Complexity: The Search for Order in a Chaotic World*, by **Peter Coveney and Roger Highfield**:

Complexity is the study of the behavior of macroscopic collections of such units that they are endowed with the potential to evolve in time.

They distinguish between mathematical complexity defined in terms of the number of mathematical operations needed to solve a problem and scientific complexity as defined above. Mathematical complexity is the sort of complexity of interest in computer science.

9. **John Sterman, *Business Dynamics: Systems Thinking and Modeling for a Complex World*.**

His underlying world view is system dynamics, emphasizing the multi-loop, multi-state, nonlinear character of the feedback systems in which we live. He says that natural and human systems have a high degree of dynamic complexity. He emphasizes that complexity is not caused simply by the number of components in a system or the number of combinations one must consider in making a decision. The latter is combinatorial complexity, finding the optimal solution from a very, very large number of possibilities.

But dynamic complexity can occur in simpler systems with little combinatorial complexity, because of interactions of the agents over time.

Time delays between taking a decision and its effects on the state of the system are common and particularly troublesome. Most obviously, delays reduce the number of times one can cycle around the learning loop, slowing the ability to accumulate experience, test hypotheses, and improve.

Dynamic complexity not only slows the learning loop, it reduces the learning gained on each cycle. In many cases controlled experiments are prohibitively costly or unethical. More often, it is simply impossible to conduct controlled experiments. Complex systems are in disequilibrium and evolve. Many actions yield irreversible consequences. The past cannot be compared well to current circumstance. The existence of multiple interacting feedbacks means it is difficult to hold other aspects of the system constant to isolate the effect of the variable of interest; as a result many variables simultaneously change, confounding the interpretation of changes in systems behavior and reducing the effectiveness of each cycle around the learning loop.

Delays also create instability in dynamic systems. Adding time delays to negative feedback loops increases the tendency for the system to oscillate. [An example:] driving a car involve[s] time delays between the initiation of a control action (accelerating/braking,) and its effects on the state of the system. As a result, decision makers often continue to intervene to correct apparent discrepancies between the desired and actual state of the system even after sufficient corrective actions have been taken to restore the system to equilibrium, leading to overshoot and oscillation. The result is [for example] stop-and-go traffic. Oscillation and instability reduce our ability to control for confounding variables and discern cause and effect, further slowing the rate of learning.

Dynamic Complexity arises because systems are

- **Dynamic:** Heraclitus said, All is change. What appears to be unchanging is, over a longer time horizon, seen to vary. Change in systems occurs at many time scales, and these different scales sometimes interact.
- **Tightly Coupled:** The actors in the system interact strongly with one another and with the natural world. Everything is connected to everything else.
- **Governed by feedback:** Because of the tight couplings among actors, our actions feed back on themselves. Our decisions alter the state of the world, causing changes in nature and triggering others to act, thus giving rise to a new situation which then influences our next decisions. Dynamics arise from these feedbacks.
- **Nonlinear:** Effect is rarely proportional to cause, and what happens locally in a system (near the current operating point) often does not apply in distant regions (other states of the system). Nonlinearity also arises as multiple factors interact in decision making: Pressure from the boss for greater achievement increases your motivation and work effort -- up to the point where you perceive the goal to be impossible.
- **History-dependent:** Taking one road often precludes taking others and determines where you end up (path dependence). Many actions are irreversible: You can't unscramble an egg (the second law of thermodynamics). Stocks and flows (accumulations) and long time delays often mean doing and undoing have fundamentally different time constants
- **Self-organizing:** The dynamics of systems arise endogenously and spontaneously from their structure. Often, small, random perturbations are amplified and molded by the feedback structure, generating patterns in space and time and creating path dependence.
- **Adaptive:** The capabilities and decision rules of the agents in complex systems change over time. Evolution leads to selection and proliferation of some agents while others become extinct. Adaptation also occurs as people learn from experience, especially as they learn new ways to achieve their goals in the face of obstacles. Learning is not always beneficial, however.
- **Counterintuitive:** In complex systems cause and effect are distant in time and space while we tend to look for causes near to the events we seek to explain. Our attention is drawn to the symptoms of difficulty rather than the underlying cause. High leverage policies are often not obvious.
- **Policy Resistant:** The complexity of the systems in which we are embedded overwhelms our ability to understand them. The result: many obvious solutions to problems fail or actually worsen the situation.
- **Characterized by tradeoffs:** Time delays in feedback channels mean the long run response of a system to an intervention is often different from its short run response. High leverage policies often cause worse-before-better behavior, while low leverage policies often generate transitory improvement before the problem grows worse.

10. **Charles Perrow, *Normal Accidents: Living with High-Risk Technologies*.**

Perrow argues that our systems have become so complex and closely coupled that accidents are normal and cannot be assured against. He discusses the idea of components being joined by complex interactions, so that the failure of one affects many others. He discusses a common-mode component being used for several purposes (e.g., a pump) so that when it fails, a number of difficult-to-predict interactions occur. Further, these components are tightly coupled, so that failures propagate through the system quickly (and perhaps not visibly).

He uses the word *linear* to contrast with *complex* when he describes interactions among subsystems (or components). By *linear* he means interactions occur in an expected sequence. By *complex* he means they may occur in an unexpected sequence.

He says complex systems are characterized by:

- Proximity of components that are not in a production sequence
- Many common mode connections between components in a production sequence
- Unfamiliar or unintended feedback loops
- Many control parameters with potential interactions
- Indirect or inferential information sources
- Limited understanding of some processes

So if complex systems have safety issues, why not make them linear? It is because we strive for the performance we can achieve only through complexity.

Tightly coupled systems are characterized by:

- Delays are not possible
- Sequence of events are invariant
- Alternative paths not available
- Little opportunity for substitution or slack
- Redundancies are designed in and deliberate

So he plots various systems of the following axes indicating a continuum in these characterizations -- far from binary.

INTERACTIONS

		LINEAR	COMPLEX
<u>COUPLING</u>	TIGHT	Dams	Nuclear Plant Airplanes
	LOOSE	Post Office	R&D Firms Universities

Adapted from *Normal Accidents: Living with High-Risk Technologies*

e.g.: Universities are loose because if something goes wrong, there is plenty of time to recover. Interconnections have long time-constants since universities are the antithesis of command and control.

Perrow explains why complex, tightly-coupled systems have normal accidents. Because the system is complex, we need decentralized operations to achieve flexibility if something goes wrong. However, tightly-coupled systems need centralized operations for system control. Clearly, we cannot have both decentralized and centralized operations, hence the inevitability of normal accidents.

11. Joseph Sussman, *Introduction to Transportation Systems*.

We speak of Complex, Large-Scale, Integrated, Open Systems, or CLIOS

A system is complex when it is composed of a group of related units (subsystems), for which the degree and nature of the relationships is imperfectly known. Its overall emergent behavior is difficult to predict, even when subsystem behavior is readily predictable. The time-scales of various subsystems may be very different (as we can see in transportation -- land-use changes, for example, vs. operating decisions). Behavior in the long-term and short-term may be markedly different and small changes in inputs or parameters may produce large changes in behavior.

Complexity can be

- Behavioral: in the sense that the emergent behavior is difficult to predict and may be counterintuitive even after the fact
- Internal: in the sense that, the structure of the system makes the system very difficult to change without causing system failure (after Moses)

- Evaluative: in the sense that the existence of many different stakeholders with different viewpoints about system performance makes it difficult to reach decisions about systems design

CLIOS have impacts that are large in magnitude, and often long-lived and of large geographical extent.

Subsystems within CLIOS are integrated, closely coupled through feedback loops.

By open, we mean that CLIOS explicitly include social, political and economic aspects.

Often CLIOS are counterintuitive in their behavior. At the least, developing a model that will predict their performance can be very difficult to do. Often the performance measures for CLIOS are difficult to define and, perhaps even difficult to agree about, depending upon your viewpoint. In CLIOS there is often human agency involved.

Transportation as an example of a CLIOS:

Transportation systems are complex, dynamic, and internally interconnected as well as interconnected with other complex dynamic systems.

They vary in space and time (at different scales for different components). Service is provided on complex networks. Systems are stochastic in nature.

Human decision-makers with complex decision calculi make choices that shape the transportation system.

Modeling the entire system is almost unthinkable. Our challenge is to choose relevant subsystems and model them appropriately for the intended purpose, mindfully reflecting the boundary effects of the unmodeled components.

SOCIAL/TECHNICAL SYSTEMS

12. Complexity in internal management of a system (like the space program) vs. complexity in the objectives of a social system -- the space program had a simple objective -- a man on the moon and back safely by the end of the 1960s. To quote from **J. Morley English (ed.)** in *Economics of Engineering and Social Systems* -- It may have been the proper order to develop the complex management systems first while holding to the straight-forward objective that the space program afforded and only then extending the systems engineering methodology to handle the more complex objectives of social systems.

13. From *Rescuing Prometheus* by **Thomas P. Hughes**:

Social scientists and public intellectuals defined the baffling social complexity to which the systems approach enthusiasts believed they could respond as a problem involving indeterminacy, fragmentation, pluralism, contingency, ambivalence, and nonlinearity. Ecologists, molecular biologists, computer scientists and organizational theorists also found themselves in a world of complex systems. Humanists -- architects and literary critics among them -- see complexity as a defining characteristic of a postmodern industrial world.

Hughes discussing **Jay Forrester** as follows:

Forrester warns decision-makers that intuitive judgements about cause-and effect relationships may not be effective in complex feedback systems, such as an urban system, with their multiple feedback loops and levels. Complex systems have a multitude of interactions, not simply cause-and-effect relationships. Causes may not be proximate in time and space to effects: a decision to increase the availability of housing, for instance, can affect the level of underemployment years later, not unlike the butterfly/chaos effect. A seemingly more proximate cause, such as the shutting down of factories, may hide the effects of the earlier decision to build more housing.

14. **Paul Ormerod, *Butterfly Economics: A New General Theory of Social and Economic Behavior***. Ormerod discusses complex economic and social systems and focuses on:

- The behavior of individuals being affected by other individuals
- How simple individual rules of behavior lead to complex behavior at the system level
- The inherent unpredictability of the short-run behavior of economic and other social systems
- And hence the futility and perhaps counter-productivity of government intervention to try to influence inflation or unemployment (e.g.)
- Thinking about the economy, not as a machine, but as a biological system

BUSINESS/ORGANIZATIONS/POLICY

15. From *The Economist*, June 5, 1999, an article entitled **Complex Equations**:

The article discusses complexity management in the context of banks and insurers, referencing work by Tim Wright of Booz-Allen & Hamilton (BAH).

Consolidation of these firms brings nightmarish complexity that undoes any cost saving or revenue synergies. But why, says BAH. These consolidations are supposed to achieve economies of scale. But while metrics like cost/call fall by 18% as calls double, such economies of scale at the operational level tend to be wiped out by diseconomies of scale at a firm-wide level. So while makers of ball-bearings, e.g., become more efficient with size, banks and insurers tend not to

Reasons customers are not one-size-fits-all, so scale economies are hard to attain. International operations are all different -- regulations, etc.

16. From *The Social Psychology of Organizations* by **Daniel Katz and Robert Louis Kahn**:

The authors note that it is a big mistake to use biological metaphors to describe patterned human activity. Further the authors say, The biological structures are anchored in physical and physiological constancies, whereas social structures are not. So don't use the physical model, because you will miss the essential social-psychological facts of the highly variable, loosely affiliated character of social systems. And a social system has no structure apart from its functioning (Allport) and is characterized by more variability than biological systems. To reduce human variability in organizations we use environmental pressures, shared values and expectations, and rule enforcement.

17. **A. O. Hirschman and C. E. Lindblom, Economic Development, Research and Development, Policy Making: Some Converging Views**, *Behavioral Science*, vol. 7 (1962), pp. 211-22.

The authors consider the three fields of interest noted in the title, each of which can be characterized as a *complex* system in the social-political-economic realm. They essentially argue that in each of these areas (drawing on the work of others), that unbalanced growth, apparently irrational strategies like duplication of resources and confusion and lack of communication may in fact be effective strategies in this context. Lindblom (in his earlier work) argues that there is a fallacy in thinking that public policy questions can best be solved by attempting to understand them and that there is almost never sufficient agreement to provide adequate criteria for choosing among possible alternative policies. He goes on to discuss what he calls disjointed incrementalism, where no attempt at comprehensiveness is made in policy-making. He argues that comprehensive policy-making in complex systems will always fail because of value conflicts, information

inadequacies and general complexity beyond man's intellectual capacities.

So in looking at these three fields of interest, the authors, in contemplating design and decision-making within these socially-based complex systems, have the following points of convergence in approaches to economic development, research and development, and policy:

- 1) The most obvious similarity is that all insist on the rationality and usefulness of certain processes and modes of behavior which are ordinarily considered to be irrational, wasteful, and generally abominable.
- 2) The three approaches thus have in common an attack on such well-established values as orderliness (see Hirschman's model of optimum disorderliness), balance, and detailed programming; they all agree with Burke that some matters ought to be left to a wise and salutary neglect .
- 3) They agree that one step ought often to be left to lead to another, and that it is unwise to specify objectives in much detail when the means of attaining them are virtually unknown.
- 4) All agree further that in rational problem solving, goals will change not only in detail but in a more fundamental sense through experience with a succession of means-ends and ends-means adjustments.
- 5) All agree that in an important sense a rational problem solver wants what he can get and does not try to get what he wants except after identifying what he wants by examining what he can get.
- 6) There is also agreement that the exploration of alternative uses of resources can be overdone, and that attempts at introducing explicitly certain maximizing techniques (trade-offs among inputs or among outputs, cost-benefit calculations) and coordinating techniques will be ineffective and quite possibly harmful in some situations. In a sense more fundamental than is implied by theories stressing the cost of information, the pursuit of certain activities that are usually held to be the very essence of economizing can at times be decidedly uneconomical.
- 7) One reason for this is the following: for successful problem solving, all agree it is most important that arrangements exist through which decision-makers are sensitized and react promptly to newly emerging problems, imbalances, and difficulties; this essential ability to react and to improvise readily and imaginatively can be stultified by an undue preoccupation with, and consequent pretense at, advance elimination of these problems and difficulties through integrated planning.
- 8) Similarly, attempts at foresight can be misplaced; they will often result in complicating the problem through mistaken diagnoses and ideologies. Since man

has quite limited capacities to solve problems and particularly to foresee the shape of future problems, the much maligned hard way of learning by experiencing the problems at close range may often be the most expeditious and least expensive way to a solution.

- 9) Thus we have here theories of successive decision-making; denying the possibility of determining the sequence *ex ante*, relying on the clues that appear in the course of the sequence, and concentrating on identification of these clues.

18. **David Levy, Applications and Limitations of Complexity Theory in Organizational Theory and Strategy, *Handbook of Strategic Management*.**

The complexity paradigm rejects some key assumptions of traditional neoclassical economics, such as perfect information, diminishing returns, and the implicit existence of a single rational agent acting on behalf of an organization to maximize some objective function. ...More pertinent is the behavioral and administrative approach to organization theory pioneered by Simon and Cyert and March, which recognizes that organizations comprise networks of people with bounded rationality.

physical systems are shaped by unchanging natural laws, whereas social systems are subject to intervention by cognizant agents, whose behavior is essentially unpredictable at the individual level. Investigations of economic time series by chaos theorists have usually assumed that relationships among economic actors are fixed over time. In reality, methods of macroeconomic management have changed from the use of the gold standard to Keynesian demand management and, later, to monetarist controls. Human agency can alter the parameters and very structures of social systems; indeed, one of the main purposes of management is to limit the gyrations of chaotic systems, reduce their sensitivity to external shocks, and, in the case of Demming's lean management systems, ensure that behavior is non-chaotic by reducing variability throughout the system.

Implications of Complexity Theory for Strategy

A. Long-term planning is impossible

Chaos theory has demonstrated how small disturbances multiply over time because of non-linear relationships and feedback effects. As a result, such systems are extremely sensitive to initial conditions, making their future states appear random. Networks, even when in the ordered regime, are subject to perturbations from external influences, which sometimes cause substantial, though unpredictable, reconfigurations.

B. Dramatic change can occur unexpectedly

Traditional paradigms of economics and strategy, built upon simplified assumptions of cause and effect, would suggest that small changes in parameters

should lead to correspondingly small changes in the equilibrium outcome. Complexity theory forces us to reconsider this conclusion. Large fluctuations can be generated internally by deterministic chaotic systems, and small perturbations to networks, even when in the ordered state, can sometimes have major effects.

C. Complex systems exhibit patterns and short-term predictability

Social scientists are generally more interested in the order than the randomness of complex systems. Short-term forecasting is possible in a chaotic deterministic system because, given a reasonable specification of conditions at one time period, we can calculate the conditions the next time period.

- D. Organizations can be tuned to be more innovative and adaptive.** Rather than expend large amounts of resources on forecasting for unpredictable futures, many writers have suggested that businesses emphasize flexibility, creativity and innovation in response to the vagaries of the marketplace. The idea that organic structures are more effective than mechanistic ones in coping with turbulent environments, does, of course, have a long pedigree in management studies. Complexity theory suggests that organic networks poised on the edge of chaos might give rise to self-organization and emergent order that enable firms to prosper in an era of rapid change.

It is important to acknowledge that complexity cannot simply be imported from the natural sciences and applied off-the-shelf to industries and firms.

Complexity theory is not a complete break from traditional organization theory and scientific methods, in that it can be seen as a continuation and deepening of systems and behavioral approaches to organization theory.

In dynamic systems, we seek webs of causation rather than simple linear relationships, and accept the inherent complexity of economic systems rather than rely on traditional reductionist frameworks.

COMPLEX ADAPTIVE SYSTEMS/SELF-ORGANIZATION

19. **John H. Holland, *Hidden Order: How Adaptation Builds Complexity***. Holland is from the Santa Fe school of complexity (**Gell-Mann**, et al.) He starts with basic elements: agents, meta-agents and adaptation and the idea of complex adaptive systems (cas). His metaphor is evolutionary biology although his examples are more broadly drawn, such as a large city. He defines four properties -- aggregation, nonlinearity, flows and diversity and three mechanisms -- tagging, internal models and building blocks. He develops the idea of adaptive agents, rules and emergence and finally a software model called echo based on sites, resources and strings which he uses on some simple cases to show how organization emerges.

He agrees we are far from a theory of cas but says a theory will probably be based on

- Interdisciplinarity
- Computer-based thought experiments
- A correspondence principle (Bohr) -- our models should encompass standard models from prior studies in relevant disciplines.
- A mathematics of competitive processes based on recombination -- Ultimately, we need rigorous generalizations that define the trajectories produced by the interaction of competition and recombination. An appropriate mathematics must depart from traditional approaches to emphasize persistent features of the far-from-equilibrium evolutionary trajectories generated by recombination.

20. **W. Brian Arthur, *On the Evolution of Complexity*** -- in *Complexity: Metaphors, Models, and Reality*, G. A. Cowan, David Pines and David Meltzer (eds.).

Arthur speaks about three ways in which systems become more complex as they evolve.

First, he discusses ecosystems (which may be organizational as well as biological in nature) in which individuals find niches within a complex web to fill. He uses the pre- and post-automobile transportation industry as an example. In the pre- period, buggy whip factories, etc., exploited niches; then the auto was invented and this quickly simplified the system, only to see it become more complex over time. He cites Newton simplifying greatly the approach of Ptolemy, the latter based on a geocentric model of the solar system with tremendous complexity introduced to make it work. Newton, with a few laws, developed the simple ideas which govern the solar-centric model and which had greatly superior predictive power.

Second, Arthur discusses structural deepening, noting that to enhance performance, subsystems are added. This refers to individuals (not ecosystems) becoming more complex. The original design of the gas-turbine had one moving part. Then to enhance performance, complexity -- subsystems -- were added.

Third, he discusses complexity and evolution through capturing software like electricity

or the mathematics of derivative trading on the financial market.

21. **Stuart Kauffman, *At Home in the Universe: The Search for the Laws of Self-Organization and Complexity*.**

Kauffman is of the Santa Fe School. His framework is biology, primarily. He thinks that Darwin's chance and gradualism cannot have been enough of a theory of evolution to get us where we are today. He writes about self-organizing systems as the additional and necessary piece of the puzzle.

While autocatalytic networks arise spontaneously and naturally because of the laws of complexity, perhaps natural selection then tunes their parameters until they are in the ordered regime near this edge -- the transitional region between order and chaos where complex behavior thrives. After all, systems capable of complex behavior have a decided survival advantage, and thus natural selection finds its role as the molder and shaper of the spontaneous order for free. In the chaotic regime, similar initial states tend to become progressively more dissimilar, and hence to *diverge* farther and farther apart in state space, as each passes along its trajectory. This is just the butterfly effect and sensitivity to initial conditions. Small perturbations amplify. Conversely, in the ordered regime, similar initial states tend to become more similar, hence *converging* closer together as they flow along their trajectories. This is just another expression of homeostasis. Perturbations to nearby states damp out

It is far too early to assess the working hypothesis that complex adaptive systems evolve to the edge of chaos. Should it prove true, it will be beautiful. But it will be equally wonderful if it proves true that complex adaptive systems evolve to a position somewhere in the ordered regime near the edge of chaos. Perhaps such a location on the axis, ordered and stable, but still flexible, will emerge as a kind of universal feature of complex adaptive systems in biology and beyond.

Further, what is the source of these properties, this ability to evolve? Is evolution powerful enough to *construct* organisms that are able to adapt by mutation, recombination, and selection? Or is another source of order -- spontaneous self-organization -- required?

It is fair to say that Darwin simply assumed that gradual improvement was possible in general. He based his argument on the selection carried out by breeders of cattle, pigeons, dogs, and other domesticated plants and animals. But it is a long, long step from selection by hand for alternation in ear shape to the conclusion that all features of complex organisms can evolve by the gradual accumulation of useful variations.

Darwin's assumption was almost certainly wrong. It does not appear to be the case that gradualism always holds. In some complex systems, any minor change causes catastrophic changes in the behavior of the system. In these cases, as we will soon discuss, selection cannot assemble complex systems. Here is one fundamental limit to selection. There is a second fundamental limit as well. Even when gradualism does hold in the sense

that minor mutations cause minor changes in phenotype, it still does not follow that selection can successfully accumulate the minor improvements. Instead, an error catastrophe can occur. An adapting population then accumulates a succession of minor catastrophes rather than a succession of minor improvements. Even with selection sifting, the order of the organism melts silently away.

Selection, in short, is powerful but not all-powerful. Darwin might have realized this were he familiar with our present-day computers.

Evolving a serial computer program is either very hard or essentially impossible because it is incredibly fragile. Familiar computer programs are precisely the kind of complex systems that do not have the property that small changes in structure yield small changes in behavior. Almost all small changes in structure lead to catastrophic changes in behavior. Furthermore, this problem becomes worse as redundancy is squeezed out of the program in order to achieve a minimal program to perform the algorithm. In a nutshell, the more compressed the program, the more catastrophically it is altered by any minor change in the instructions. Hence the more compressed the program, the harder it is to achieve by any evolutionary search process.

And yet the world abounds with complex systems that have successfully evolved -- organisms, economies, our legal system. We should begin to ask, What kinds of complex systems can be assembled by an evolutionary process? I should stress that no general answer is known, but that systems with some kinds of redundancy are almost certainly far more readily evolved than those without redundancy. Unfortunately, we only roughly understand what redundancy actually means in evolving systems.

COMPLEXITY -- SOME SHORT TAKES [N.B.: often my paraphrases]

Gordon Allport: Social systems are more contrived than biological systems and have no dependable life cycle.

W. Brian Arthur, *On the Evolution of Complexity* -- in *Complexity: Metaphors, Models, and Reality*, G. A. Cowan, David Pines and David Meltzer (eds.): In evolving systems, bursts of simplicity often cut through growing complexity and establish new bases upon which complexity can then grow.

Jay Forrester: In complex feedback systems, apparent causes may in fact be coincident interactions.

John Holland, *Hidden Order: How Adaptation Builds Complexity*: Adaptable systems become complex.

Thomas P. Hughes, *Rescuing Prometheus*: Humanists -- architects and literary critics among them -- see complexity as a defining characteristic of a postmodern industrial world.

Stuart Kauffman, *At Home in the Universe: The Search for the Laws of Self-Organization and Complexity*: The reason complex systems exist on, or in the ordered regime near the edge of chaos is because evolution takes them there.

David Levy, *Applications and Limitations of Complexity Theory in Organizational Theory and Strategy, Handbook of Strategic Management*: Complexity theory is not a complete break from traditional organization theory and scientific methods, in that it can be seen as a continuation and deepening of systems and behavioral approaches to organization theory.

Joel Moses, *Complexity and Flexibility*: Our view of complexity differs from that of the man on the street. Complexity is not an inherently bad property to us. Rather it is the coin of the realm in systems. You usually have to expend complexity dollars to achieve useful goals, such as increased functionality, efficiency or flexibility.

Charles Perrow, *Normal Accidents: Living with High-Risk Technologies*: If complex systems have safety issues, why not make them linear? It is because we strive for the performance we can achieve only through complexity.

Eberhardt Rechtin and Mark Maier, *The Art of System Architecting*: qualitatively different problem-solving techniques are required at higher levels of complexity than at low ones.

This primacy of complexity is system design helps explain why a single optimum seldom, if

ever, exists for such systems. There are just too many variables.

Herbert Simon, *The Architecture of Complexity*: It may not be entirely vain, however, to search for common properties among diverse kinds of complex systems.

Evolution favors the hierarchically organized. Hierarchy leads to redundancy to the decomposability of hierarchically-organized units -- which offers the hope that complexity can be fairly simply described.

John Sterman, *Business Dynamics: Systems Thinking and Modeling for a Complex World*: dynamic complexity can occur in simpler systems with little combinatorial complexity, because of interactions of the agents over time.

Joseph Sussman, *Introduction to Transportation Systems*: Complexity can be

- Behavioral: in the sense that the emergent behavior is difficult to predict and may be counterintuitive even after the fact
- Internal: in the sense that, the structure of the system makes the system very difficult to change without causing system failure (after Moses)
- Evaluative: in the sense that the existence of many different stakeholders with different viewpoints about system performance makes it difficult to reach decisions about systems design

Edward Tenner, *Why Things Bite Back: Technology and the Revenge of Unintended Consequences*: In complex systems, actions may be counter-productive. When one works to avoid catastrophe in complex systems, one engenders chronic problems.

John Von Neumann: Redundancy is a complex system's way of dealing with failure.

M. Mitchell Waldrop, *Complexity: The Emerging Science at the Edge of Order and Chaos*: Learning and evolution move agents along the edge of chaos in the direction of greater and greater complexity.

natural selection is *not* the antagonist of self-organization. It's more like a law of motion -- a force that is constantly pushing emergent, self-organizing systems toward the edge of chaos.

Edward O. Wilson, *Consilience: The Unity of Knowledge*: Complexity theory is defined as the search for algorithms used in nature that display common features across many levels of organization.

SOME OVERARCHING QUESTIONS

Does a living-organism/ecosystem analogy lead us in the right direction for understanding complexity in engineering systems and organizational/social systems?

Is it possible to make good predictions of short-run behavior of complex systems?

Is optimization a realistic (or even defined) goal for complex systems?

If evolution to the edge between order and chaos is right, what does that imply for optimization of complex systems?

For systems beyond some degree of complexity, are accidents inevitable?

If complexity is the path to performance but may also degrade system safety, how does one make that trade-off (evaluative complexity)?

Was Darwin right or wrong (or at least incomplete) in his explanation of evolution? Is self-organization a necessary adjunct to Darwin's theory?

Does some underlying explanatory theory of complex systems, cutting across such systems of many (or even all) types, exist?

Would such a theory necessarily involve building up from a reductionist understanding of components to overall emergent behavior of the overall system?

And, finally: *Is complexity theory an appropriate underlying theme for ESD?*

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