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IDEAS ON COMPLEXITY IN SYSTEMS

-- TWENTY VIEWS

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IDEAS ON COMPLEXITY IN SYSTEMS -- TWENTY VIEWS

The purpose of this note is to catalogue the ideas of a number of systems thinkers in the area of complexity. I have either quoted directly or done my best to properly paraphrase these ideas. I hope that this note will be useful as we begin to think through the "discipline" of engineering systems to be developed by the ESD faculty.

AUTHOR	SOURCE
Joel Moses	"Complexity and Flexibility" (working paper)
Peter Senge	*The Fifth Discipline* (book)
Joseph Sussman	"The New Transportation Faculty: The Evolution to Engineering Systems" (paper) *Introduction to Transportation Systems* (book)
J. Morley English	*Economics of Engineering and Social Systems* (book)
Rechtin and Maier	*The Art of System Architecturing* (book)
Flood and Carson	*Dealing with Complexity* citing Vemuri in *Modeling of Complex Systems* (book)
Coveney and Highfield	*Frontiers of Complexity* (book)
The Economist (6/5/99)	"Complex Equations" (magazine)
Edward O. Wilson	*Consilience: The Unity of Knowledge* (book)
Katz and Kahn	*The Social Psychology of Organization* (book)
Tom Hughes	*Rescuing Prometheus* (book)
David Warsh	*The Idea of Economic Complexity* (book)
John H. Holland	*Hidden Order: How Adaptation Builds Complexity* (book)
David Levy	"Applications and Limitations of Complexity Theory in Organizational Theory and Chapters" (book chapter)
A. O. Hirschman and C. E. Lindbloom	"Economic Development, Research and Development, Policy Making: Some Divergent Views" (paper)
W. Brian Arthur	"On the Evolution of Complexity" (book chapter)
Murray Gell-Mann	"Complex Adaptive Systems" (book chapter)
Charles Perrow	*Normal Accidents: Living with High-Risk Technologies* (book)

John Sterman	*Business Dynamics* (book in preparation)
Stuart Kauffman	*At Home in the Universe: The Search for the Laws of Self-Organization and Complexity* (book)

These are various concepts, in no particular order.

1. Complexity as per **Joel Moses in his memo "Complexity and Flexibility"**, which uses node and link structures.

   "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."

2. Detail complexity vs. dynamic complexity as per **Peter Senge in "The Fifth Discipline"**, page 71:

   "…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.

3. Complexity as in **CLIOS (Sussman, "The New Transportation Faculty: The Evolution to Engineering Systems",** ***Transportation Quarterly*****, Summer 1999):**

   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.

   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.

   Joseph M. Sussman, **Introduction to Transportation Systems**, Artech House Publishers, Inc., Boston, MA, April 2000.

   Transportation as an example:

   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.

4. 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 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.

5. Complexity as per **Rechtin and Maier in "The Art of System Architecting"**, page 7, 8:

   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 is system design helps explain why a single 'optimum' seldom, if ever, exists for such systems. There are just too many variables."

6. From **"Dealing with Complexity", by Flood and Carson, after Vemuri in "Modeling of Complex Systems", 1978, New York: Academic Press.**

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) * "Open" here is NOT as used by Sussman.

7. From **"Frontiers of Complexity" by Coveney and 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."

   He distinguishes 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.

8. 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 BAH -- Tim Wright in the London office.

   "… 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.

9. From **“Consilience: The Unity of Knowledge” by Edward O. Wilson**:

   This book is a tour-de-force, working toward tying together much of what is known and will be known.

   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 is simplest terms is the great challenge of scientific holism.” (bold mine)**

   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”.

   So it will be much harder in biology, he suggests. He says that simply because a theory predicts emergent behavior at a systems level, that does NOT mean the steps used in that prediction are “necessarily the same as those that exist in the real world”.

   He defines complexity theory “as the search for algorithms used in nature the display common features across many levels of organization”. He says this theory “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”.

10. From **“The Social Psychology of Organizations” by Katz and Kahn** (provided to me by Tom Allen):

    They note that it is a big mistake to use biological metaphors to describe patterned human activity (**Allport**). “Social systems are more contrived and biological systems and have no dependable life cycle.” 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.

The authors cite **Boulding** describing 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"

They cite **von Bertananffy** who proposed "the idea of a general system theory that would embrace all levels of science from the study of a single cell to the study of a society". His theory is based on an "open" energic input-output system.

The authors state, "System theory is basically concerned with problems of relationships, of structure and of interdependence rather than the constant attributes of objects. In general approach, it resembles field theory except that its dynamics deal with temporal as well as spatial patterns."

11. From **"Rescuing Prometheus" by Tom 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 **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. Forrester points out that in complex feedback systems, apparent causes may in fact be coincident interactions.

12. From **"The Idea of Economic Complexity" by David Warsh** (the Boston Globe columnist) -- his ideas on economic complexity don't add much to our mix, suggesting that economic complexity is fundamentally hierarchical. He does include some useful characterizations of the thinking of others:

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

    Herbert Simon—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.

    Here again we wonder if a living-system definition of complexity leads us in the right direction for engineering systems and especially organizational questions.

13. **John H. Holland** -- **Hidden Order: How Adaptation Builds Complexity** -- Holland is from the Santa Fe school of complexity. (**Gell-Mann**, et al.). This is a good little book that captures much useful thinking. He starts with "basic elements": agents, meta-agents and adaptation and the idea of 'cas', which stands for complex adaptive systems. His metaphor is evolutionary biology although his examples are more broadly drawn, such as a large city -- indeed, that is his first example. He defines 4 properties -- aggregation, nonlinearity, flows and diversity and 3 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.”

One key idea: adaptable systems become complex!

14. **David Levy, UMASS/Boston** has several papers **“Applications and Limitations of Complexity Theory in Organizational Theory and Strategy”** to appear in “Handbook of Strategic Management”, and **“Chaos Theory and Strategy: Theory, Application, Management Implications”**, Strategic Management Journal, Vol. 15 (1994). I quote from the former:

“Comparing Chaos and Complexity Theory

Both chaos and complexity theory attempt to reconcile the essential unpredictability of non-linear dynamic systems with a sense of underlying order and structure. There are, however, some significant differences between the two approaches. Chaos theory searches for a small number of deterministic mathematical functions driving a system; in population models, for example, these functions might represent the fluctuations in the numbers of a species. Network theory is less concerned with underlying simplicity; it tends to rely on brute computing power to model large numbers of nodes connected by simple logical rules. Network theory is more interested in the emergent order and patterns in complex systems rather than trying to find a simple mathematical “engine” in the system. Network models often try to capture the essence of interaction among the many agents in a system while chaos theory generally attempts to model some resultant outcome, such as prices or investment.

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 (1957) and Cyert and March** (1963), which recognizes that organizations comprise networks of people with bounded rationality.

To understand the relevance of complexity to strategy, we need to conceptualize industries as dynamic, non-linear systems. **As Stacey (1995:480) puts it, "nonlinearity and positive feedback loops are fundamental properties of organizational life".** BOLD MINE -- Much of the industrial organization aspect of strategy literature concerns itself with how firms interact with each other and with other actors in their environment, such as consumers, labor, the government, and financial institutions. These interactions are strategic in the sense that decisions by one actor take into account anticipated reactions by others, and thus reflect a recognition of interdependence…

As **(Michael) Porter** (1990) emphasizes, the evolution of industries is dynamic and path dependent: corporate (and country-level) capabilities acquired during previous competitive episodes shape the context for future competitive battles. Moreover, the accumulation of competitive advantage can be self-reinforcing, through processes related to standard setting and economies of scale, suggesting important sources of non-linearity…

…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 **(Womack and Jones, 1990),** 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 (**Burns and Stalker, 1961**). 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 **(Allen, 1988; Brown and Eisenhardt, 1997**).

Conclusions

This paper has provided a basic description of complexity, distinguishing between chaos theory and network analysis. Dynamic non-linear systems with feedback mechanisms can exhibit complex, unpredictable behavior within which underlying patterns and structure can be discerned. A working knowledge of the relevant theory and terminology of complexity is essential for readers to be able to make their own judgements concerning the application of complexity to social science in general and strategy in particular.

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.”

15. 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’ [1958, p. 80]), 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."

16. W. Brian Arthur, **On the Evolution of Complexity** -- in Complexity by Cowens, Pines and 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 preperiod, 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 notes that, "In evolving systems, bursts of simplicity often cut through growing complexity and establish new bases upon which complexity can then grow." 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.

17. Murray Gell-Mann, **Complex Adaptive Systems** -- in Complexity by Cowens, Pines and Meltzer (eds.).

In an article on complex adaptive systems (CAS), Gell-Mann discusses the CAS cycle.

" When we ask general questions bout the properties of CAS, as opposed to questions about specific subject matter such as computer science, immunology, economics, or policy matters, a useful way to proceed, in my opinion, is to refer to the parts of the CAS cycle.

I. coarse graining,

II. identification of perceived regularities,

III. compression into a schema,

IV. variation of schemata,

V. application of schemata to the real world,

VI. consequences in the real world exerting selection pressures that affect the competition among schemata,

as well as four other sets of issues:

VII. comparisons of time and space scales,

VIII. inclusion of CAS in other CAS,

IX. the special case of humans in the loop (directed evolution, artificial selection), and

X. the special case of composite CAS consisting of many CAS (adaptive agents) constructing schemata describing one another's behavior.

Here, in outline form, is an illustrative list, arranged according to the categories named, of a few features of CAS, most of them already being studied by members of the Santa Fe Institute family, that seem to need further investigation:

I. Coarse Graining

1. Tradeoffs between coarseness for manageability of information and fineness for adequate picture of the environment.

II. Sorting Out of Regularities from Randomness

1. Comparison with distinctions in computer science between intrinsic program and input date.

2. Possibility of regarding the elimination of the random component as a kind of further coarse graining.

3. Origin of the regularities in the fundamental laws of nature and in shared causation by past accidents; branching historical trees and mutual information; branching historical trees and thermodynamic depth.

4. Even in an infinite data stream, it is impossible to recognize all regularities.

5. For an indefinitely long data stream, algorithms for distinguishing regularities belonging to a class.

6. Tendency of a CAS to err in both directions, mistaking regularity for randomness and vice versa.

III. Compression of Perceived Regularities into a Schema

1. If a CAS is studying another system, a set of rules describing that system is a schema; length of such a schema as effective complexity of the observed system.

2. Importance of potential complexity, the effective complexity that may be achieved by evolution of the observed system over a given period of time, weighted according to the probabilities of the different future histories; time best measured in units reflecting intervals between changes in the observed system (inverse of mutation rate).

3. Tradeoffs between maximum feasible compression and lesser degree that can permit savings in computing time and in time and difficulty of execution; connection with tradeoffs in communication theory -- detailed information in data base versus detailed information in each message and language efficiency versus redundancy for error correction.

4. Oversimplification of schema sometimes adaptive for CAS at phenotypic (real world) level.

5. Hierarchy and chunking in the recognition of regularities.

IV. Variation of Schemata

1. In biological evolution, as in many other cases, variation always proceeds step by step from what already is available, even when major changes in organization occur; vestigial features and utilization of existing structures for new functions are characteristic; are there CAS in which schemata can change by huge jumps all at once?

2. Variable sensitivity of phenotypic manifestation to different changes in a schema; possibility in biological case of long sequences of schematic changes with little phenotypic change, followed by major phenotypic ‘punctuations;’ generality of this phenomenon of ‘drift.’

3. Clustering of schemata, as in subspecies and species in biology or quasispecies in theories of the origin of life or word order patterns in linguistics -- generality of clustering.

4. Possibility, in certain kinds of CAS, of largely sequential rather than simultaneous variants.

V. Use of the Schema (Reexpansion and Application to Real World)

   1. Methods of incorporation of (largely random) new data.
   2. Description, prediction, prescribed behavior -- relations among these functions.
   3. Sensitivity of these operations to variations in new data.

VI. Selection Pressures in the Real World Feeding Back to Affect Competition of Schemata

   1. Concept of CAS still valid for systems in which ‘death’ can be approximately neglected and reproduction and population may be correspondingly unimportant.
   2. Exogenous fitness well-defined, as in a machine to play checkers; when endogenous, a elusive concept: attempts to define it in various fields, along with seeking maxima on ‘landscapes.’
   3. Noise, pauses for exploration, or other mechanisms required for the system to avoid getting stuck at minor relative maxima; survey or mechanisms employed by different systems.
   4. Procedures to use when selection pressures are not derivable from a fitness function, as in neural nets with (realistic) unsymmetrical coefficients.
   5. Possible approaches to the case of coevolution, in which the fitness concept becomes even more difficult to use.
   6. Situations in which maladaptive schemata occur because of mismatch of time scales.
   7. Situations in which maladaptive schemata occur because the system is defined too narrowly.
   8. Situations in which maladaptive schemata occur by chance in a CAS operating straightforwardly.

VII, VIII. Time Scales; CAS Included in Others or Spawned by Others

   1. Problems involved in describing interactions among CAS related by inclusion or generation and operating simultaneously on different levels and on different time scales.

IX. CAS with Humans in the Loop

1. Information about the properties of sets of explicit and implicit human preferences revealed by such systems.

X. CAS Composed of Many Coadapting CAS

1. Importance of region between order and disorder for depth, effective complexity, etc.
2. Possible phase transition in that region.
3. Possibility of very great effective complexity in the transition region.
4. Possibility of efficient adaptation in the transition region.
5. Possibility of relation to self-organized criticality.
6. Possible derivations of scaling (power law) behavior in the transition region.
7. With all scales of time present, possibility of universal computation for the system in the transition region."

18. 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. One idea of his is 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 though 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 occur in an unexpected sequence.

So 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 of inferential information sources
- Limited understanding of some processes

So if complex systems may have some safety issues, why not make them linear? 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

COUPLING	**LINEAR**	**COMPLEX**
TIGHT	**Dams**	**Nuclear Plant** **Airplanes**
LOOSE	**Post Office**	**R&D Firms** **Universities**

NB: 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.

19. John Sterman, in his book in preparation on **Business Dynamics**.

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:** Herablitus 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."

20. 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.

"… I will present evidence for an idea that I will more fully develop in the next chapter: *the reason complex systems exist on, or in the ordered regime near, the edge of chaos is because evolution takes them there.* While autocatalytic networks arise spontaneously and naturally because of the laws of complexity, perhaps natural selection then tunes their parameters, tweaking the dials for *K* and *P*, 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." We measure average convergence or divergence along the trajectories of a network to determine its location on the order-chaos axis. In fact, in this measure, networks at the phase transition have the axis. In fact, in this measure, networks at the phase transition have the property that nearby states neither diverge nor converge.

... What we have found for the modestly complex behaviors we are requesting is that the networks do adapt and improve and that they evolve, not to the very edge of chaos, but to the ordered regime, not too far from the edge of chaos. It is as though a position in the ordered regime near the transition to chaos affords the best mixture of stability and flexibility.

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 or 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, I will try to show, 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. We will discuss error catastrophe later in the chapter.

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.

…

Patch Possibilities

I find it fascinating that hard problems with many linked variables and loads of conflicting constraints can be well solved by breaking the entire problem into nonoverlapping domains. Further, it is fascinating that as the conflicting constraints become worse, patches become ever more helpful.

While these results are new and require extension, I suspect that patching will, in fact, prove to be a powerful means to solve hard problems. In fact, I suspect that analogues of patches, systems having various kinds of local autonomy, may be a fundamental mechanism underlying adaptive evolution in ecosystems, economic systems, and cultural systems. If so, the logic of patches may suggest new tools in design problems. Moreover, it may suggest new tools in the management of complex organizations and in the evolution of complex institutions world-wide.

Homo sapiens sapiens, wise man, has come a long way since bifacial stone axes. We are constructing global communication networks, and whipping off into space in fancy tin cans powered by Newton’s third law. The *Challenger* disaster, brownouts, the Hubble trouble, the hazards of failure in vast linked computer networks -- our design marvels press against complexity boundaries we do not understand. I wonder how general it has become as we approach the year 2000 that the design of complex artifacts is plagued with nearly unsolvable conflicting constraints. One hears tales, for example, of attempts to optimize the design of complex manufactured artifacts such as such as supersonic transports. One team optimizes airfoil characteristics, another team optimizes seating, another works on hydraulics, but the multiple solutions do not converge to a single compromise that adequately solves all the design requirements. Proposals keep evolving chaotically. Eventually, one team makes a choice -- say, how the hydraulic system or the airfoil structure will be constructed -- and the rest of the design becomes frozen into place because of this choice.

Does this general problem of nonconvergence reflect “patching” the design problem into too many tiny patches such that the overall design process is in a nonconverging chaotic regime, just as would be our 120 x 120 lattice broken into 5 x 5 rather than 6 x 6 patches? If one did not know that increasing patch size would lead from chaos to ordered convergence on excellent solutions, one would not know to try “chunking” bigger. It seems worth trying on a variety of real-world problems.

Understanding optimal patching may be useful in other areas in the management of complex organizations. For example, manufacturing has long used fixed facilities of interlinked production processes leading to a single end product. Assembly-line production of manufactured products such as automobiles is an example. Such fixed facilities are used for long production runs. It is now becoming important to shift to flexible manufacturing. Here the idea is to be able to specify a diversity of end products, reconfigure the production facilities rapidly and cheaply, and thus be able to carry out short production runs to yield small quantities of specialized products for a variety of niche markets. But one must test the output for quality and reliability. How should this be done? At the level of each individual production step? At the level of output of the entire system? Or at some intermediate level of chunking? I find myself thinking that there may be an optimal way to break the total production process in each case into local patches…”