Unifying Principles in Complex Systems

Yaneer Bar-Yam
New England Complex Systems Institute
24 Mt. Auburn St., Cambridge, MA 02138

Introduction

Implications of Complex Systems and Converging Technologies for Human Performance

The ability of science and technology to augment human performance depends on an understanding of systems, not just components. The convergence of technologies is an essential aspect of the effort to enable functioning systems that include human beings and technology; and serve the human beings to enhance their well-being directly and indirectly through what they do, and what they do for other human beings. The recognition today that human beings function in teams, rather than as individuals, implies that technological efforts that integrate human beings across scales of tools, communication, biological and cognitive function are essential.

Understanding the role of complex systems concepts in technology integration requires a perspective on how the concept of complexity is affecting science, engineering, and finally, technology integration.

Complex systems and science

The structure of scientific inquiry is being challenged by the broad relevance of complexity to the understanding of physical, biological and social systems[1-3]. Cross-disciplinary interactions are giving way to trans-disciplinary and unified efforts to address the relevance of large amounts of information to description, understanding and control of complex systems. From the study of biomolecular interactions[4-7] to the strategy and tactics of 21st Century Information Age Warfare and the War on Terrorism[8-14], complexity has arisen as a unifying feature of challenges to understanding and action. In this arena of complex systems, information and action, structure and function are entangled. New approaches that recognize the importance of patterns of behavior, the multiscale space of possibilities, and evolutionary or adaptive processes that select systems or behaviors that can be effective in a complex world are central to advancing our understanding and capabilities[15,16].

Complex systems and engineering

The failure of design and implementation of a new air-traffic control system[17], failures of Intel processors[18], medical errors[19,20], failures of medical drugs[21,22], even the failure of the Soviet Union, can be attributed to large system complexities. Systematic studies of large scale engineering projects have revealed a remarkable proportion of failures in major high investment projects[23]. The precursors of such failures: multisystem integration, high performance constraints, many functional demands, high rates of response, and large context specific protocols, are symptomatic of complex engineering projects. The methods for addressing and executing major engineering challenges must begin from the recognition of the central role of complexity and the modern tools that can guide the design, or self-organize, highly complex systems. Central to effective engineering is the evaluation of the complexity of function of a system, and the recognition of fundamental engineering tradeoffs of structure, function, complexity and scale in system capabilities, and the application of indirection to specification, design and control of system development and the system itself.

Defining complex systems and complex tasks[15]

One way to identify a complex task is as a problem where the number of distinct possibilities that must be considered, anticipated or dealt with is substantially larger than can be reasonably named or enumerated. Intuitively, the complexity of a task is the number of wrong choices for every right choice. We can casually consider in an explicit way tens of possibilities, a professional will readily deal with hundreds of possibilities, and a major project will deal with thousands, the largest projects deal with tens of thousands. For larger numbers of possibilities we must develop new strategies. Simplifying a complex task by ignoring the need for different responses is what leads to errors or failures that affect the success of the entire effort, leaving it as a gamble with progressively higher risks.

The source of complex tasks is complex systems. Complex systems are systems with interdependent parts. Interdependence means that we cannot identify the system behavior by just considering each of the parts and combining them. Instead we must consider how the relationships between the parts affect the behavior of the whole. Thus a complex task is also one for which many factors must be considered to determine the outcome of an action.

While complex systems give rise to complex tasks, reliable responses to complex tasks can only be achieved by complex systems. Thus, the complex challenges that we face in the world can be met only by the development of complex systems that can address them.

Converging Technologies

The rapid development of nanotechnology and the convergence of biological, information, and cognitive sciences is creating a context in which complex systems concepts that enable effective organizations to meet complex challenges can be realized through technological implementation. At the same time, complex systems concepts and methods are an essential part of the framework in which this convergence is taking place. From the fine scale control of systems based upon nanotechnology to understanding the system properties of the integrated socio-technical system consisting of human beings and computer information networks, the synergy of complex systems and converging technologies is apparent as soon as we consider the transition between components and functions.

Looking forward

Human civilization, its various parts, including its technology, and its environmental context, are all complex. The most reliable prediction possible is that this complexity will continue to increase. The great opportunity of the convergence of nanotechnology, biomedical, information, and cognitive sciences is an explosive increase in what is possible through combining advances in all areas. This is, by definition, an increase in the complexity of the systems that will be formed out of technology and of the resulting behaviors of people who use them directly, or are affected by them. The increasing complexity suggests that there will be a growing need for widespread understanding of complex systems as a counter point to the increasing specialization of professions and professional knowledge. The insights of complex systems research and its methodologies may become pervasive in guiding what we build, how we build it, and how we use and live with it. Possibly the most visible outcome of these developments will be an improved ability of human beings aided by technology to address complex global social and environmental problems, third world development, poverty in developed countries, war and natural disasters. At an intermediate scale, the key advances will dramatically change how individuals work together in forming functional teams that are more directly suited to the specific tasks they are performing. In the context of individual human performance, the key to major advances is recognizing that the convergence of technology will lead to the possibility of designing (more correctly adapting) the environment of each individual for his or her individual needs and capabilities in play and work.

The practical need

Complex systems studies range from detailed studies of specific systems, to studies of the mechanisms by which patterns of collective behaviors arise, to general studies of the principles of description and representation of complex systems. These studies are designed to enable us to understand and modify complex systems, design new ones for new functions or create contexts in which they self-organize to serve our needs without direct design or specification. The need for applications to biological, cognitive, social, information, and other engineered systems is apparent.

Biology has followed an observational and reductionistic approach of accumulating large bodies of information about the parts of biological systems, and looking for interpretations of system behavior in terms of these parts. It has become increasingly clear that biological systems are intricate spatially structured biochemically based networks. The role of information in biological action and the relationships of structure and function are only beginning to be probed by mathematicians, physicists and engineers who are interested in biological systems as systems designed by nature for their functional capabilities. While biologists are increasingly looking to mathematical approaches and perspectives developed in physics and engineering, engineers are increasingly looking to biological systems for inspiration in designing artificial systems. Underlying these systems are a wealth of design principles in areas that include the biochemical networks[3-7], immune systems[24-27] and neural systems[28-30], and animal behaviors such as the swimming mechanisms of fish[31] and the gaits of animals[32]. These systems and architectures point to patterns of function that have a much higher robustness to failure and error and a higher adaptability than conventional human engineered systems.

Computers have made a transition from systems with tightly controlled inputs and outputs to systems that are networked and responding on demand as part of interactive information systems[33]. This has changed radically the nature of the issues facing their design. The collective behaviors of these networked computer systems, including the internet, limit their effectiveness. Whether these have to do with the dynamics of packet loss in internet traffic[34], or the effect of computer viruses or worms[35-38], that, at times, have incapacitated a large fraction of the internet, these effects are not small. The solution to these problems is understanding collective behaviors and designing computer systems to be effective in environments with complex demands and to have a higher robustness to attack.

The human brain is often considered the paradigmatic complex system. The implications of this recognition are that cognitive function is distributed within the brain and mechanisms may vary from individual to individual. Complete explanations of cognitive function must themselves be highly complex. Major advances in cognitive science are currently slowed by a combination of efforts to explain cognitive function directly from the behavior of individual molecular and cellular components, and on the other hand by aggregating or averaging the cognitive mechanisms of different human beings. Still, diverse advances that are being made are pointing the way to improvements in education[39], man-machine interfaces[40-42] and retention of capabilities during aging[43-46].

The War in Afghanistan has demonstrated that both the fundamental strategy and the mechanisms and opportunities for achieving goals in complex conflicts differ qualitatively from those of conventional large scale conflicts as manifest in the Gulf War. The recognition of the complexity of conflict in the War on Terrorism is another indication that the basic concept of complexity in social systems or problems has begun to be recognized[8-14]. Unfortunately, this understanding has yet to be transferred to address other diverse major fundamental social system problems, as found in medical system cost containment, education system reform, and alleviation of poverty in this country. In each case, current approaches continue to be dominated by large scale strategies that are not effective in addressing complex problems. Even with the appearance of more holistic approaches to, e.g. third world development[47,48], the basic concept of existing strategy remains weakly informed by complex systems insights. This gap is an opportunity for major contributions by the field of complex systems both at the conceptual and technical levels. Further contributions can be made based upon research projects that emphasize the intrinsic complexity of these systems.

Understanding global physical and biological systems is also a major challenge in complex systems. Many of the key problems today have to do with “indirect effects” of human activities that may have substantial destructive effects on the human condition. These include global warming, and ecological deterioration due to overexploitation of resources. Effective approaches to these problems will require an understanding of both the environmental and socioeconomic implications of our current actions, and of actions that are designed to alleviate these problems[49]. For example, the problem of global warming includes the effects of large scale human activity interacting with both the linear and potentially non-linear climactic response. Despite the grave risks associated with global warming, a key factor impeding actions to alleviate it are fears of major impacts of such efforts on socioeconomic systems. Better understanding of the potential effects of such interventions should enable considered actions to be taken.

Interest

The current applicability and potential of complex systems research has led to a widespread interest that has attracted the attention of corporations as well as the public. Corporations recognize the complexity of their environments, the complexity of their own organizational structures and functions, the complexity of innovation and design, as well as the complexity of specific products and services they provide[50,51]. Complex systems has become recognized as the basic scientific endeavor whose inquiry has relevance to the management of complex organizations in a complex world[52]. More specific attention has been gained in information technology[53], biotechnology[54-57], healthcare industries[58] and the military[8-14].

Information technology companies building computer hardware and software have begun to recognize the inherently interactive and distributed nature of systems they are designing. A significant example is the IBM "Autonomic Computing" initiative[53], which is inspired by the biological paradigm of the autonomic nervous system and is conceptually based upon modeling robustness through biologically inspired system design. A different perspective has been demonstrated by Apple Computer in showing the relevance of human factors ranging from hardware design, to ease-of-use, to creativity facilitation as essential aspects of the role of computers in computer/human systems.

The major advances in biotechnology, including the genome project and other high throughput data acquisition methods, have led to a dramatic growth in the importance of modeling and representation tools to capture these large bodies of information and relate them to system descriptions and properties. Many private companies at the forefront of biotechnology are developing bioinformatics tools that strive to relate information to functional descriptions also described as "functional genomics[54]." This is one facet of a broader recognition of the importance of capturing the multiscale properties of biological systems as reflected in the biocomplexity initiative of the NSF[55] and the complex biological systems programs at the NIH[56], and joint programs[57].

For several years, the interest in complex systems as a conceptual and quantitative management tool has led consulting companies to work on practical implementations of strategy and more specific modeling efforts[59,60]. One of the areas of particular interest has been in the healthcare management community where rapid changes in organizations has led to a keen interest in complex systems insights[58].

In the military and intelligence communities, there has been an increasing realization of the relevance of networked distributed control and information systems. Each of the branches of the military and the joint chiefs of staff has adopted vision statements that focus on complex systems concepts and insights as guiding the development of plans for information age warfare[8-14]. These concepts affect both the engineering of military sensors, effectors, and information networks, and the underlying nature of military force command and control.

More broadly, the attention of the public has been widely attracted to the description of complex systems research and insights. Indeed, many popular descriptions of complex systems research existed before the first textbook was written[61-70]. While these popularized descriptions do not capture many of the technical advances, they do capture the excitement of inquiry that reflects the growth of this new field. The excitement of scientists as well as the public reflects the potential impact on our ability to understand questions that affect everyday life, perspectives on the world around us, fundamental philosophical disputes, and issues of public concern including major societal challenges, the dynamics of social networks, global computer networks (the WWW), biomedical concerns, psychology and ecology.

The goals

The goals of complex systems research are to:

- Understand the development and mechanisms of patterns of behavior and their use in engineering.
- Understand the way to deal with complex problems (engineering, management, economic, sociopolitical) with strategies that relate the complexity of the challenge to the complexity of the system that must respond to them.
- Understand the unifying principles of organization, particularly for systems that deal with large amounts of information (physical, biological, social and engineered).
- Understand the interplay of behaviors at multiple scales, and between the system and its environment.
- Understand what is universal and what is not, when averaging applies and when it does not, what can be known and what cannot, what are the classes of universal behavior and the boundaries between them, and what are the relevant parameters for description or for affecting the behavior of the system.
- Develop the ability to capture and represent specific systems, rather than just accumulate data about them. In this context: to describe relationships, know key behaviors, recognize relevance of properties to function, and to simulate dynamics and response.
- Achieve a major educational shift toward unified understanding of systems, and patterns of system behavior.

The traditional approach of science to take things apart and assign the properties of the system to its parts has been quite successful, but the limits of this approach have become apparent in recent years. When properties of a system result from dependencies and relationships but we assign them to their parts, major obstacles to understanding and control arise. Once the error of assignment is recognized, some of the obstacles can be overcome quickly, while others become subject of substantive inquiry. While many scientists think that the parts are universal, but the way parts work together is specific to each system it has become increasingly clear that how parts work together can also be studied in general and by doing so we gain insight into every kind of system that exists, physical systems like the weather, as well as biological, social and engineered systems.

Understanding complex systems does not mean that we can predict their behavior exactly, it is not just about massive databases, or massive simulations, even though these are important tools of research in complex systems. The main role of research in the study of complex systems is recognizing what we can and cannot say about complex systems given a certain level (or scale) of description, and how we can generalize across diverse types of complex systems. It is just as important to know what we can know, as to know. Thus the concept of deterministic chaos appears to be a contradiction in terms: how can a deterministic system also be chaotic? It is possible because there is a rate at which the system behavior becomes dependent on finer and finer details[71-75]. Thus, how well we know that system at a particular time, determines how well we can predict its behavior over time. Understanding complexity is neither about prediction or lack of predictability, but rather a quantitative knowledge of how well we can predict, and only within this constraint, what the prediction is.

Fundamental research in complex systems:

Fundamental research in complex systems is designed to obtain characterizations of complex systems and relationships between quantities that characterize them. When there are well defined relationships, these are formalized as theorems or principles, more general characterizations and classifications of complex systems are described below in major directions of inquiry. These are only a sample of the ongoing research areas.

Theorems and principles of complex systems:

A theorem or principle of complex systems should apply to physical, biological, social and engineered systems. Similar to laws in physics, a law in complex systems should relate various quantities that characterize the system and its context. An example is Newton's 2nd law that relates force, mass and acceleration. Laws in complex systems relate qualities of system, action, environment, function and information. Three examples follow.

A) Functional complexity

Given a system whose function we want to specify, for which the environmental (input) variables have a complexity of $C(e)$, and the actions of the system have a complexity of $C(a)$, then the complexity of specification of the function of the system is:

$$C(f)=C(a)\ 2^{C(e)}$$

Where complexity is defined as the logarithm (base 2) of the number of possibilities or, equivalently, the length of a description in bits. The proof follows from recognizing that a complete specification of the function is given by a table whose rows are the actions (C(a) bits) for each possible input, of which there are $2^{C(e)}$. Since no restriction has been assumed on the actions, all actions are possible and this is the minimal length description of the function. Note that this theorem applies to the complexity of description as defined by the observer, so that each of the quantities can be defined by the desires of the observer for descriptive accuracy. This theorem is known in the study of Boolean functions (binary functions of binary variables) but is not widely understood as a basic theorem in complex systems[15].

The implications of this theorem are widespread and significant to science and engineering. The exponential relationship between the complexity of function and the complexity of environmental variables implies that systems that have environmental variables (inputs) with more than a few bits (i.e. 100 bits or more of relevant input) have functional complexities that are greater than the number of atoms in a human being, and thus cannot be reasonably specified. Since this is true about most systems that we characterize as "complex" the limitation is quite general. The implications are that fully phenomenological approaches to describing complex systems, such as the behaviorist approach to human psychology, cannot be successful. Similarly, the testing of response or behavioral descriptions of complex systems cannot be performed. This is relevant to various contexts from the testing of computer chips, today with over 100 bits of input, to testing of the effects of medical drugs in double blind population studies, today used in various combinations with various quantities for synergistic effects, with a need to avoid harmful drug interactions. In each case the number of environmental variables (inputs) is large enough that all cases cannot be tested.

B) Requisite variety

The Law of Requisite Variety states: The larger the variety of actions available to a control system, the larger the variety of perturbations it is able to compensate[76]. Quantitatively, it specifies that the probability of success of a well adapted system in the context of its environment can be bounded:

$$-\mathrm{Log}_2(P) < C(e) - C(a)$$

Qualitatively, this theorem specifies the conditions in which success is possible: a matching between the environmental complexity and the system complexity, where success implies regulation of the impact of the environment on the system.

The implications of this theorem are widespread in relating the complexity of desired function to the complexity of the system that can succeed in the desired function. This is relevant to discussions of the limitations of specific engineered control system structures, to the limitations of human beings and of human organizational structures.

Note that this theorem, as formulated, does not take into account the possibility of avoidance (actions that compensate for multiple perturbations because they anticipate and thus avoid the direct impact of the perturbations), or the relative measure of the space of success to that of the space of possibilities. These limitations can be compensated for.

C) Non averaging

The Central Limit Theorem specifies that collective/aggregate properties of *independent* components with bounded probability distributions are Gaussian distributed with a standard deviation that diminishes as the square root of the number of components. This simple solution to the collective behavior of non-interacting systems does not extend to the study of interacting/interdependent systems. The lack of averaging of properties of complex systems is a statement that can be used to guide the study of complex systems more generally. It also is related to a variety of other formal results, including Simpson's paradox[77] which describes the inability of averaged quantities to characterize the behavior of systems, and Arrow's Dictator Theorem which describes the generic dynamics of voting systems[78,79].

The lack of validity of the Central Limit Theorem has many implications that affect experimental and theoretical treatments of complex systems. Many studies rely upon unjustified assumptions in averaging observations that lead to misleading if not false conclusions. The development of approaches that can identify the domain of validity of averaging and use more sophisticated approaches (like clustering) when they do not apply, are essential to progress in the study of complex systems.

Another class of implications of the lack of validity of the Central Limit Theorem is the recognition of the importance of individual variations between different complex systems even when they appear to be within a single class. An example mentioned above is the importance of individual differences and the lack of validity of averaging in cognitive science studies. While snowflakes are often acknowledged as individual, research on human beings often is based on assuming their homogeneity.

More generally, we see that the study of complex systems is concerned with their universal properties, and one of their universal properties is individual differences. This apparent paradox, one of many in complex systems (see below), reflects the importance of identifying when universality and common properties apply and when they do not, a key part of the universal study of complex systems.

Major Directions of inquiry:

A) Understanding self-organization and pattern formation, and how it can be used to form engineered systems.

Self-organization is the process by which elements interact to create spatio-temporal patterns of behavior that are not directly imposed by external forces. To be concrete, consider the patterns on animal skins, spontaneous traffic jams and heart beats. For engineering applications, the promise of understanding such pattern formation is the opportunity to use the natural dynamics of the system to create structures and impose functions, rather than to construct them element by element. The robustness of self-organized systems is also a desired, and difficult to obtain, quality in conventional engineered systems. For biomedical applications, the promise is to understand developmental processes like the development of the fertilized egg into a complex physiological organism, like a human being. In the context of the formation of complex systems through development or through evolution, elementary patterns are the building blocks of complex systems. This is diametrically opposed to considering parts as the building blocks of such systems.

Spontaneous (self-organizing) patterns arise through symmetry breaking in a system when there are multiple inequivalent static or dynamic attractors. In general, in such systems, a particular element of a system is affected by forces from more than one other element and this gives rise to "frustration" as elements respond to aggregate forces that are not the same as each force separately. Frustration contributes to the existence of multiple attractors and therefore of pattern formation.

Pattern formation can be understood using simple rules of local interaction, and there are identifiable classes of rules (universality) that give rise to classes of patterns. These models can be refined for more detailed studies. A useful illustrative example of pattern forming processes is: Local-activation long-range inhibition models which can describe patterns on animal skins, magnets, dynamics of air flows in clouds, wind driven ocean waves, and swarm behaviors of insects and animals. Studies of spontaneous and persistent spatial pattern formation were initiated by Turing[80] the wide applicability of patterns has gained increasing interest in recent years[15,81-85].

The universality of patterns has been studied in statistical physics, where dynamic patterns arise in quenching to a first order phase transition, for cases of both conserved (spinodal decomposition, e.g. oil-water separation) and non-conserved order parameters (coarsening, e.g. freezing water)[86], and in growing systems (self-organized criticality[87], roughening[88]). Generic types of patterns are relevant for such contexts and are distinguished by their spatio-temporal behaviors. Classic models have characteristic spatial scales (Turing patterns, coarsening, spinodal-decomposition), others are scale invariant (self-organized criticality, roughening). Additional classes of complex patterns arise in networks with long range interactions (rather than just spatially localized interactions) and are used for modeling spin glasses[89], neural networks[28-30] or genetic networks[90].

B) Understanding description and representation

The study of how we describe complex systems is itself an essential part of the study of such systems. Since science is concerned with describing reproducible phenomena and engineering is concerned with the physical realization of described functions, description is essential to both. A description is some form of identified map of the "actual" system onto a mathematical or linguistic object. Shannon's information theory[91] has taught us that the notion of description is linked to the space of possibilities. Thus, while description appears to be very concrete, any description must reflect not only what is observed but also an understanding of what might be possible to see. An important practical objective is to capture information and create representations that allow human or computer based inquiry into the properties of the system.

Among the essential concepts relevant to the study of description is the role of universality and non-universality[92] as a key to the classification of systems and of their possible representations. In this context, rather than studying a single model of a system, effective studies are those that identify the class of models that can capture properties of a system. Related to this issue is the problem of testability of representations through the validation of the mapping of the system to the representation. Finally, the practical objective of achieving human-usable representations must grapple with the finite complexity of a human being, and other human factors due to both "intrinsic" properties of complex human function and the "extrinsic" properties that are due to the specific environment in which human beings have developed their sensory and information processing systems.

The issue of human factors can be understood more generally as part of the problem of identifying the observer's role in description. A key issue is identifying the scale of observation: the level of detail that can be seen by an observer, or the degree of distinction between possibilities[56,15]. Effective descriptions have a consistent precision so that all of the necessary but not a lot of unnecessary information is used, irrelevant details are eliminated but all relevant details are included. A multiscale approach[15] relates the notion of scale to the properties of the system, and relates descriptions at different scales.

The key engineering challenge is to relate the characteristics of a description to function. This involves relating the space of possibilities of the system to the space of possibilities of the environment (variety, adaptive function). Complexity is a logarithmic measure of the number of possibilities of the system, equivalently the length of the description of a state. The Law of Requisite Variety[76] limits the possible functions of a system of a particular complexity.

C) Understanding evolutionary dynamics

The formation of complex systems, and the structural/functional change of such systems, is the process of adaptation. Evolution[93] is the adaptation of populations through intergenerational changes in the composition of the population (the individuals of which it is formed) and learning is a similar process of adaptation of a system through changes in its internal patterns, including but not exclusively, the changes in its component parts.

Characterizing the mechanism and process of adaptation, both evolution and learning, is a central part of complex systems research[94-95,66-68]. This research generalizes the problem of biological evolution by recognizing the relevance of processes of incremental change to the formation of all complex systems. It is diametrically opposed to the notion of creation in engineering which typically assumes that new systems are invented without precursor. The reality of incremental changes in processes of creativity and design reflect the general applicability of evolutionary concepts to all complex systems.

The conventional notion of evolution of a population based upon replication with variation and selection with competition continues to be central. However, additional concepts have become recognized as important, and are the subject of ongoing research, including the concepts of co-evolution[95], ecosystems[95], multiple niches, hierarchical or multilevel selection[96,97] and spatial populations[98]. Ongoing areas of research include the traditional philosophical paradoxes involving selfishness and altruism[99], competition and cooperation[100] and nature and nurture[101]. Another key area of ongoing inquiry is the origin of organization, including the origins of life[102], which investigate the initial processes that give rise to the evolutionary process of complex systems.

The engineering applications of evolutionary process are often mostly associated with the concept of evolutionary programming or genetic algorithms[94,103,104]. In this context evolution is embodied in a computer. Among the other examples of the incorporation of evolution into engineering are the use of artificial selection and replication in molecular drug design[105-107], and the human induced variation with electronic replication of computer viruses, worms and Trojan horses in internet attacks[38]. The importance of a wider application of evolution in management and engineering is becoming apparent. The essential concept is that evolutionary processes may enable us to form systems that are more complex than we can understand but will still serve functions that we need. When high complexity is necessary for desired function the system should be designed for evolvability: e.g. Smaller components (subdivided modular systems) evolve faster[108]. We note, however, that in addition to the usual concept of modularity, evolution should be understood to use patterns, not elements, as building blocks. The reason for this is that patterns are more directly related to collective system function and are therefore testable in a system context.

D) Understanding choices and anticipated effects: Games and agents

Game theory[109-112] explores the relationship between individual and collective action using models where there is a clear statement of consequences (individual payoffs), that depend on the actions of more than one individual. A paradigmatic game is the ‘prisoners dilemma.’ Traditionally, game theory is based upon logical agents that make optimal decisions based upon full knowledge of the possible outcomes, though these assumptions can be usefully relaxed. Underlying game theory is the study of the role of anticipated effects on actions and the paradoxes that arise because of contingent anticipation by multiple anticipating agents, leading to choices that are undetermined within the narrow definition of the game, and thus sensitive to additional properties of the system. Game theory is relevant to fundamental studies of various aspects of collective behavior: altruism and selfishness and cooperation and competition. It is relevant to our understanding of biological evolution, socio-economic systems and societies of electronic agents. At some point in increasing complexity of games and agents the models become agent based models directed at understanding specific systems.

E) Understanding generic architectures:

The concept of a network as capturing aspects of the connectivity, accessibility or relatedness of components in a complex system is widely recognized as important in understanding aspects of these systems. So much so, that many names of complex systems include the term "network." Among the systems that have been identified thus are: artificial and natural transportation networks (roads, railroads, waterways, airways)[113-116], social networks[117], military forces[8-14], the Internet[118-120], the World Wide Web[121-123], biochemical networks[4-7], neural networks[28-30], and food webs[124]. Networks are anchored by topological information about nodes and links, with additional information that can include nodal locations and state variables, link distances, capacities and state variables, and possibly detailed local functional relationships involved in network behaviors.

In recent years, there has been significant interest in understanding the role played by the abstract topological structure of networks represented solely by nodes and links[125-138]. This work has focused on understanding the possible relationships between classes of topological networks and their functional capacities. Among the classes of networks contrasted recently are locally connected, random[125,126], small-world[127-131], and scale-free networks[132-138]. Other network architectures include regular lattices, trees, and hierarchically decomposable networks[108]. Among the issues of functional capacity are: which networks are optimal by some measure, e.g., their efficiency in inducing connectivity, and the robustness or sensitivity of their properties to local/random failure or directed attack. The significance of these studies from an engineering perspective is in answering the questions such as: What kind of organizational structure is needed to perform what function with what level of reliability? What are the tradeoffs that are made in different network architectures? Determining the organizational structures and their tradeoffs is relevant to all scales and areas of the converging technologies: nanotechnology, biomedical, information and social networks.

F) Understanding (recognizing) the paradoxes of complex systems:

The study of complex systems often reveals difficulties with concepts that are used in the study of simpler systems. Among these are conceptual paradoxes. Many of these paradoxes take the form of the coexistence of properties that, in simpler contexts, appear to be incompatible. In some cases it has been argued that there is a specific balance of properties, for example the "edge-of-chaos" concept, suggesting a specific balance of order and chaos. However, in complex systems, order and chaos often coexist and this is only one example of the wealth of paradoxes that are present. A more complete list would include paired properties such as:

Stable and adaptable
Reliable and controllable
Persistent and dynamic
Deterministic and chaotic
Random and predictable
Ordered and disordered
Cooperative and competitive
Selfish and altruistic
Logical and paradoxical

Averaging and non-averaging
Universal and unique.

While these pairs describe paradoxes of properties, the most direct paradox in complex systems is a recognition that more than one "cause" can exist, so that A causes B, and C causes B are not mutually incompatible statements. The essential role of understanding paradox in complex systems is to broaden our ability to conceive of the diversity of possibilities, both for our understanding of science, and for our ability to design engineered systems that serve specific functions and have distinct design tradeoffs that do not fit within conventional perspectives.

G) Developing systematic methodologies for the study of complex systems:

While there exists a conventional "scientific method", the study of complex systems suggests that many more detailed aspects of scientific inquiry can be formalized. The existence of a unified understanding of patterns, description and evolution as relevant to the study of complex systems, suggests that we adopt a more systematic approach to scientific inquiry. Components of such a systematic approach would include experimental, theoretical, modeling, simulation and analysis strategies. Among the aspects of a systematic strategy are the capture of quantitative descriptions of structure and dynamics, network analysis, dynamic response, information flow, multiscale decomposition, the identification of modeling universality class, and the refinement of modeling and simulations.

Major application areas of complex systems research

The full richness of complex systems applications cannot be captured here, however, the following should provide a sense of the integral nature of complex systems to advances in nanotechnology, biomedicine, information technology, cognitive science, social and global systems.

Nanotechnology:

The development of functional systems based on nanotechnological control is a major challenge beyond the creation of single elements. Indeed, the success of nanotechnology in controlling small elements can synergize well with the study of complex systems. To understand the significance of complex systems for nanotechnology it is helpful to consider the smallest class of biological machines, also considered the smallest complex systems—proteins[139]. Proteins are a marvel of engineering for design and manufacture. They also have many useful qualities that are not common in artificial systems, including robustness and adaptability through selection. The process of manufacturing a protein is divided into two parts, the creation of the molecular chain, and the collapse of this chain to the functional form of the protein. The first step is ideal from a manufacturing point of view, since it enables direct manufacture from the template (RNA) which is derived from the information archive (DNA) which contains encoded descriptions of the protein chain. However, the chain that is formed in manufacture is not the functional form. The protein chain “self-organizes” (sometimes with assistance from other proteins) into its functional (folded) form. By manufacturing proteins in a form that is not the functional form, key aspects of the manufacturing process can be simplified, standardized and made efficient while allowing a large variety of functional machines described in a simple language. The replication of DNA provides a mechanism of creating many equivalent information archives (by exponential growth) that can be transcribed to create templates to manufacture proteins in a massively parallel way, when mass production is necessary. All of these processes rely upon rapid molecular dynamics. While proteins are functionally robust in any particular function, their functions can also be changed/adapted by changing the archive which “describes” their function, but in an indirect and non-obvious way. The rapid parallel process of creation of proteins allows adaptation of new machines through large scale variation and selection. A good example of this process is found in the immune system response[24-27]. The immune system maintains a large number of different proteins that serve as antibodies that can attach themselves to harmful antigens. When there is an infection, the antigens that attach most effectively are replicated in large numbers, and they are also subjected to a process of accelerated evolution through mutation and selection that generates even better suited antibodies. Since this is not the evolutionary process of organisms, it is, in a sense, an artificial evolutionary process optimized / engineered for the purpose of creating well adapted proteins / machines. Antibodies are released into the blood as free molecules, but they are also used as ‘tools’ by cells that hold them attached to their membranes so that the cells can attach to, ‘grab hold,’ of antigens. Finally, proteins also form complexes, are part of membranes and biochemical networks, showing how larger functional structures can be built out of simple machines. An artificial analog of the immune system's use of evolutionary dynamics is the development of ribozymes by in-vitro selection, now being used for drug design[105-107].

Proteins and ribozymes illustrate the crossover of biology and nanotechnology. They also illustrate how complex systems concepts of self-organization, description, and evolution are important to nanotechnology. Nanotechnological design and manufacturing may take advantage of the system of manufacture of proteins or it may use other approaches. Either way, the key insights of how proteins work shows the importance of understanding various forms of description (DNA) self-reproduction of the manufacturing equipment (DNA replication by polymerase chain reaction, or cell replication) rapid template based manufacture (RNA transcription to an amino-acid chain), self-organization into functional form (protein folding) and evolutionary adaptation through replication (mutation of DNA and selection of protein function), and modular construction (protein complexes). Understanding complex systems concepts thus will enable the development of practical approaches to nanotechnological design, manufacture, and adaptation to functional requirements of nanotechnological constructs.

Biomedical systems:

At the current time the most direct large scale application of complex systems methods is to the study of biochemical networks (gene regulatory networks, metabolic networks) that reveal the functioning of cells and the possibilities of medical intervention[4-7]. The general studies of network structure described above are complementary to detailed studies of the mechanisms and function of specific biochemical systems[140]. High throughput data acquisition in genomics and proteomics is providing the impetus for constructing functional descriptions of biological systems[54]. This, however, is only the surface of the necessary applications of complex systems approaches that are intrinsic to the modern effort to understand biological organisms, their relationships to each other, and their relationship to evolutionary history. The key to a wider perspective is recognizing that the large quantities of data that are currently being collected are being organized into databases that reflect the data acquisition process rather than the potential use of this information. The opportunities for progress will grow dramatically when the information is organized in a form that provides a description of systems and system functions. Since cellular and multicellular organisms, including the human being, are not simply biochemical soups, this description must capture the spatiotemporal dynamics of the system as well as the biochemical network and its dynamics. In the context of describing human physiology from the molecular scale, the goal of creating such a description is now being called the Virtual Human Project[141,142]. This term has also been used to describe static images of a particular person at a particular time[143].

The program of study of complex systems in biology requires not only the study of a particular organism (the human being) or a limited set of model organisms, as has been done in the context of genomics until now. The problem is to develop comparative studies of systems, understanding the variety that exists within a particular type of organism (e.g. among human beings) and the variety that exists across types of organisms. Ultimately, the purpose is to develop an understanding / description of the patterns of biological systems today as well as through the evolutionary process. The objective of understanding variety and evolution requires us to understand not just any particular biochemical system, but the space of possible biochemical systems filtered to the space of those that are found today, their general properties, their specific mechanisms, how these general properties carry across organisms and how they are modified for different contexts. Moreover, new approaches that consider biological organisms through the relationship of structure and function, and information flow are necessary to this understanding.

The increasing knowledge about biological systems is providing us with engineering opportunities and hazards. The great promise of our biotechnology is insufficient without a better understanding of systematic implications of interventions that we can do today. The frequent appearance of biotechnology in the popular press through objections to genetic engineering and cloning reveals the great specific knowledge and the limited systemic knowledge of these systems. The example of corn genetically modified for feed and its subsequent appearance in corn eaten by human beings[144] reveals the limited knowledge we have of indirect effects in biological systems. This is not a call to limit our efforts, simply to focus on approaches that emphasize the roles of indirect effects and explores their implications scientifically. Without such studies, it is not only that we are shooting in the dark, but also that we will be at the mercy of popular viewpoints.

The virtual human project would be a major advance toward models for medical intervention. Such models are necessary when it is impossible to test multidrug therapies, or specialized therapies based upon individual genetic differences. Intervention in complex biological systems is a complex problem. The narrow bridge that currently exists between medical double blind experiments and the large space of possible medical interventions can be greatly broadened through systemic models that reveal the functioning of cellular systems and their relationship to cellular function. While today individual medical drugs are tested statistically, the main fruit of models will be to reveal the relationship between the function of different chemicals and the possibility of multiple different types of interventions that can achieve similar outcomes, or the possibility of small variations in treatment that can affect the system differently, and possibly most importantly, the role of variations between human beings in the difference of response to medical treatment. A key aspect of all of these is the development of complex systems representations of biological function that reveal the interdependence of biological system and function.

Indeed, the rapid development of medical technologies, and the expectation of even more dramatic changes, should provide an opportunity for, even require, a change in the culture of medical practice. Key to these changes should be an understanding of the dynamic state of health. Conventional homeostatic perspectives on health are being modified to homeodynamic perspectives[145,146]. What is needed is a better understanding of the functional capabilities of the healthy individual—the ability of the body to respond to changes in the external and internal environment for repair or regulation. This is an essential step into enhancing the individual capability of maintaining his or her own health. For example, while aging is often considered to be a problem of elderly individuals, it is commonly known that repair and regulatory mechanisms begin to decline much earlier, e.g. in the upper 30s when professional athletes typically end their careers. By studying the dynamic response of an individual and its change over the life cycle, it should be possible to understand these early aspects of aging and to develop interventions that maintain a higher standard of health. More generally, an understanding of the network of regulatory and repair mechanisms should provide a better mechanism for monitoring, with biomedical sensors and imaging, health and disease and the impact of medical interventions. This dynamic monitoring would provide key information about the effectiveness of interventions for a particular individual, enabling feedback into the treatment process that can greatly enhance its reliability.

Information systems:

Various concepts have been advanced over the years for the importance of computers in performing large scale computations or in replacing human beings through artificial intelligence. Today the most apparent role of computers is as personal assistants and as communication devices and information archives for the socioeconomic network of human beings. The system of human beings and the internet has become an integrated whole leading to a more intimately linked system. Less visibly, embedded computer systems are performing various specific functions in information processing for industrial age devices like cars. The functioning of the internet and the possibility of future networking of embedded systems reflects the properties of the network as well as the properties of the complex demands upon it. While the internet has some features that are designed, others are self-organizing, and the dynamic behaviors of the internet reflect problems that may be better solved by using more concepts from complex systems that relate to interacting systems adapting in complex environments rather than conventional engineering design approaches.

Information systems that are being planned for business, government, military, medical and other functions are currently in a schizophrenic state where it is not clear whether distributed intranets or integrated centralized databases will best suit function. While complex systems approaches generally suggest that creating centralized databases is often a poor choice in the context of complex function, the specific contexts and degree to which centralization is useful must be understood more carefully in terms of the function and capabilities, both at the current time and in the context of adaptability to future change[11].

A major current priority is enabling computers to automatically configure themselves and carry out maintenance without human intervention[53]. Currently, computer networks are manually configured and often the role of various choices in configuring them are not clear, especially for the performance of networks. Indeed, evidence indicates that network system performance can be changed dramatically using settings that are not recognized by the users or system administrators until chance brings them to their attention[147,148]. The idea of developing more automatic processes is a small part of the more general perspective of developing adaptive information systems. This extends the concept of self-configuring and self-maintenance to endowing computer-based information systems with the ability to function effectively in diverse and variable environments. In order for this functioning to take place the ability of information systems themselves to recognize patterns of behavior in the demands upon them and in their own activity are necessary. This is a clear direction for development of both computer networks and embedded systems.

The development of adaptive information systems in networks involves the appearance of software agents. Such agents range from computer viruses to search engines and may have communication and functional capabilities that allow social interactions between them. In the virtual world of software agents, complex systems perspectives are apparent in considering such societies of agents. As only one example, the analogy of software agents to viruses and worms has also led to an immune system perspective on the design of adaptive responses[35-37].

While the information system as a system is an important application of complex systems concepts, complex systems concepts also are relevant to considering the problem of developing information systems as effective repositories of information for human use. This involves two aspects, the first is the development of repositories that contain descriptions of complex systems that human beings would like to understand. The example of biological databases in the previous section is only one example. Other examples are socio-economic systems, global systems and astrophysical systems. In each case, the key issue is to gain an understanding of how such complex systems can be effectively represented. The second aspect of designing such information repositories is the recognition of human factors in the development of human computer interfaces[40-42]. This is important in developing information repositories for human use. More generally, it is important in developing all aspects of computer based information systems that are designed explicitly or implicitly to serve human beings.

More broadly still, the networked information system that is being developed, serves as part of the human socio-economic-technological system. Various parts of this system that include human beings and information systems, and the system as a whole, is a functional system. The development/design of this self-organizing system and the role of science and technology is a clear area of application of complex system understanding and methods. Since this is a functional system, based upon a large amount of information, among the key questions is how the system be should organized when action and information are entangled.

Cognitive systems:

The decade of the 1990s was declared the “decade of the brain[149]” based, in part, on optimism that new experimental techniques such as Positron Emission Tomography (PET) imaging would provide a wealth of insights into the mechanism of the brain function. However, a comparison of the current experimental observations of cognitive processes[150] with those of biochemical processes of gene expression patterns[151] reveals the limitations that are still present in these observations in studying the complex function of the brain. Indeed, it is reasonable to argue that the activity of neurons of a human being and their functional assignment is no less complex than the expression of genes of a single human cell. Current experiments on gene expression patterns allow the possibility of knocking out individual genes to investigate the effect of each gene on the expression pattern of all other genes measured individually. The analogous capability in the context of cognitive function would be to incapacitate an individual neuron and investigate the effect on the firing patterns of all other neurons individually. Instead, neural studies are based upon sensory stimulation and measures of the average activity of large regions of cells. In the context of gene expression, many cells with the same genome and a controlled history through replication, and averages over the behavior of these cells are taken. By contrast, in neural studies averages are often taken of the activity patterns of many individuals with distinct genetic and environmental backgrounds. The analogous biochemical experiment would be to average behavior of many cells of different types from a human body (muscle, bone, nerve, red blood cell, etc.) and different individuals, to obtain a single conclusion about the functional role of the genes. The much more precise and larger quantities of genome data have revealed the difficulties in understanding genomic function and the realization that gene function must be understood through models of genetic networks[152]. This is to be contrasted with the conclusions of cognitive studies that investigate the aggregate response of many individuals to large scale sensory stimuli and infer functional assignments. Moreover, these functional assignments often have limited independently verifiable or falsifiable implications. More generally, a complex systems perspective suggests that it is necessary to recognize: the limitations of the assignment of function to individual components ranging from molecules to subdivisions of the brain, the limitations of narrow perspectives on the role of environmental/contextual effects that consider functioning to be independent of effects other than the experimental stimulus, and the limitations of expectations that human differences are small and therefore that averaged observations have meaning in describing human function.

The problem of understanding brain and mind can be understood quite generally through the role of relationships between patterns in the world and patterns of neuronal activity and synaptic change. While the physical/biological structure of the system is the brain, the properties of the patterns identify the psychofunctioning of the mind. The relationship of external and internal patterns are further augmented by relationships between patterns within the brain. The functional role of patterns is achieved through the ability of internal patterns to represent both concrete and abstract entities and processes, ranging from the process of sensory-motor response to internal dialog. This complex nonlinear dynamic system has a great richness of valid statements that can be made about it, but identifying an integrated understanding of the brain/mind system cannot be captured by perspectives that limit their approach through the particular methodologies of the researchers involved. Indeed, the potential contributions of the diverse approaches to studies of brain and mind have been limited by the internal dynamics of the many-factioned scientific and engineering approaches.

The study of complex systems aspects of cognitive systems, including the description of patterns in the world and patterns in mind, the construction of descriptions of complex systems, and the limitations on information processing that are possible for complex systems, are relevant to the application of cognitive studies to the understanding of human factors in man-machine systems[40-42], and more generally the design of systems that include both human beings and computer-based information systems as functional systems. Such hybrid systems, mentioned previously in the section on information technology, reflect the importance of the converging technology approach.

The opportunity for progress in the understanding of the function of the networked / distributed neurophysiological system also opens the possibility of greater understanding of development/learning and aging[39,43-46]. While the current policy of education reform is using a uniform measure of accomplishment and development through standardized testing, it is clear that more effective measures must be based on a better understanding of cognitive development and individual differences. The importance of gaining such knowledge is high because the evaluation of the effectiveness of new approaches to education typically requires a generation to see the impact of large scale educational changes on society. The positive or negative effects of finer scale changes appear to be largely inaccessible to current research. Thus, we see the direct connection between complex systems approaches to cognitive science and societal policy in addressing the key challenge of the education system which is linked to the solution of many other complex societal problems, including poverty, drugs and crime, and also to the effective functioning of our complex economic system requiring individuals with diverse and highly specialized capabilities.

Studies of the process of aging are also revealing the key role of environment on the retention of effective cognitive function[44-46]. The notion of ‘use it or loose it,’ similar to the role of muscular exercise, suggests that unused capabilities are lost more rapidly than used ones. While this is clearly a simplification, since losses are not uniform across all types of capabilities and overuse can also cause deterioration, it is a helpful guideline that must be expanded upon in future research. This suggests that research should focus on the effects of the physical and social environments for the elderly and the challenges that they are presented with.

We can unify and summarize the complex systems discussion of the cognitive role of the environment for children, adults and the elderly by noting that the complexity of the environment and the individual must be matched for effective functioning. If the environment is too complex, confusion and failure result, if the environment is too simple, deterioration of functional capability results. One approach to visualizing this process is to consider the internal physical parts and patterns of activity to be undergoing evolutionary selection that is dictated by the patterns of activity that result from environmental stimulation. This evolutionary approach also is relevant to the recognition that individual differences are analogous to different ecological niches. A more detailed research effort would not only consider the role of complexity but also the effect of specific patterns of environment and patterns of internal functioning, individual differences in child development, aging, adult functioning in teams and hybrid human/computer systems.

Social systems and societal challenges:

While social systems are highly complex, there are still relatively simple collective behaviors that are not well understood. These include commercial fads, panics and market cycles, bubbles and busts. Understanding the fluctuating dynamics and predictability of markets continues to be a major challenge. It is important to emphasize that complex systems studies are not necessarily about predicting the market, but about understanding its predictability or lack thereof.

More generally, there are many complex social challenges associated with complex social systems ranging from military challenges to school / education system failures and healthcare errors and problems with quality of service. Moreover, other major challenges remain in our inability to address fundamental social ills such as poverty (in developed and undeveloped countries), drugs and crime. It is helpful to focus on one of these, and the current military context is a convenient one, to clarify some aspects of social systems from a complex systems perspective.

Wars are major challenges to our national abilities. The current war on terrorism is no exception. In dealing with this challenge, our leadership, including the president and the military, recognized that this conflict is a highly complex one. Instead of just applying a large force by sending in tens to hundreds of thousands of troops, as was done in the Gulf War, there is a strategy of using small teams of special forces to gain intelligence, laying the groundwork for carefully targeted, limited and necessary force.

The contrast between the Gulf War and the War on Terrorism illustrates the difference between two types of challenges: Large scale and highly complex. Old style wars were large challenges. The biggest forces won. The most recent example, of course, is the Gulf war. The first of our really complex wars was Vietnam. Vietnam, and other conflicts, like the Soviet war in Afghanistan, taught us the difference between large and a complex wars, and to deal with each in a very different way.

A large scale challenge can be met by many individuals doing the same thing at the same time, or repeating the same action. This is like a large military force. In contrast, a complex challenge has to be met by many individuals doing many different things at different times. Each action has to directly match the local task that has to be done. The jungles of Vietnam and the mountains of Afghanistan, reported to have high mountains and deep narrow valleys, are case studies in complex terrains. War is complex when the targets are hidden, not only in the terrain but also among people; bystanders or friends. It is also complex when the enemy can itself do many different things, when the targets are diverse, and the actions that must be taken are specific and the difference between the right and wrong action is subtle.

While we are now focused on the War on Terrorism, still, it seems worthwhile to transfer the lessons we learned from different kinds of military conflicts to other areas where we are trying to solve major problems.

Over the past 20 years, the notion of war has been used to describe the War on Poverty, the War on Drugs and other national challenges. These were called wars because they were believed to be challenges requiring the large force of old style wars. They are not. They are complex challenges requiring detailed intelligence and the application of the necessary forces in the right places. Allocating large budgets for the War on Poverty did not eliminate the problem, neither does neglect. The War on Drugs has taken a few turns, but even the most recent social campaign

"Just Say No" is a large scale approach. Despite positive intentions, we have not won these wars because we are using the wrong strategy.

There are other complex challenges that we have dealt with using large forces. Third world development is the international version of the War on Poverty to which the World Bank and other organizations have applied large forces. Recently more thoughtful approaches are being taken, but they have not gone far enough. There is a tendency to fall into the 'central planning trap'. When challenges become complex enough, even the very notion of central planning and control fails. Building functioning socioeconomic systems around the world is such a complex problem that it will require many people taking small and targeted steps---like the special forces in Afghanistan.

There are other challenges that we have not, yet, labeled wars, which are also suffering from the same large force approach. Among these are cost containment in the medical system and effectiveness of the education system.

In the medical system the practice of cost controls through managed care is a large force approach that started in the early 1980s. Today, the medical system quality of care is disintegrating under the stresses/turbulence generated by this strategy. Medical treatment is clearly one of the most complex tasks we are regularly engaged in. Across the board cost control should not be expected to work.

We are just beginning to apply the same kind of large scale strategy to the education system through standardized testing. Here again a complex systems perspective suggests that the outcomes will not be as positive as the intentions. Children, after all, are engaged in the complex task of preparing themselves for the complex world we live in.

The wide applicability of the lessons learned from fighting complex wars, and the effective strategies that resulted, should be further understood through research projects that can better articulate the relevant lessons and how they pertain to solving the many and diverse complex social problems we face.

Global and larger systems:

Global systems, physical, biological and social, are potentially the most complex systems that are studied by science today. The possibility of advancing in our understanding of them by using a conventional approach of decomposition to elements appears to be particularly limited in addressing these systems. Even large scale simulations of physical systems, such as those used in meteorological prediction achieve accurate prediction over a relatively short period of time. Thus, complex systems methods that can provide tools for analyzing their large scale behavior are particularly relevant. Geophysical and geobiological systems, including meteorology, plate tectonics and earthquakes, river/drainage networks, the biosphere and ecology, have been the motivation for and the application of complex systems methods and approaches[116,153-157]. Such applications also extend to other planets, solar and astrophysical systems.

Among the key problems in studies of global systems is understanding the indirect effects of global human activity which in many ways has reached the scale of the entire earth / biosphere. The possibility of human impact on global systems through overexploitation or other byproducts of industrial activity has become a growing socio-political concern. Of particular concern are the impacts of human activity on the global climate (climate change and global warming), on the selfsustaining properties of the biosphere through over-exploitation and depletion of key resources (loss of biodiversity, deforestation, loss of specific food resources like fish, depletion of energy resources like petroleum). Other global systems include the global societal problems, that can include the possibility of global economic fluctuations, societal collapse and terrorism. Our effectiveness in addressing these questions will require a greater level of understanding and representations of indirect effects, and the knowledge of what are effective mechanisms for intervention, if necessary. In this context, the objective is to determine which aspects of a system can be understood or predicted based upon available information, and the level of uncertainty in such predictions. In some cases, the determination of risk or uncertainty is as important as the prediction of the expected outcome. Indeed, knowing "what is the worst that can happen" is often an important starting point for effective decision making.

In general, the ability of humanity to address these global problems must rely upon the collective behavior of people around the world. Global action is now almost standard in everything from local natural disasters (earthquakes, floods, volcanoes, droughts) to man-made problems from wars (Gulf War, Bosnia, Rwanda, the War on Terrorism), to environmental concerns (international agreements on environment and development).

There is a different sense in which addressing global concerns will require the participation of many individuals: the high complexity of these problems implies that many individuals must be involved in addressing these problems and they must be highly diverse and yet coordinated. Thus, the development of complex systems using convergent technologies that facilitate human productivity and cooperative human functioning will be necessary to meeting these challenges.

What is to be done?

The outline above of major areas of complex systems research and applications provides a broad view in which many specific projects should be pursued. We can, however, single out three tasks that, because of their importance or scope, are worth identifying as priorities for the upcoming years: Education; a set of key system descriptions; and a highly complex engineering project designed as an evolutionary system.

The importance of education in complex systems concepts for all areas of science, technology and society at large has been mentioned above but should be emphasized. There is need for educational materials and programs that convey complex systems concepts and methods and are accessible to a wide range of individuals, and more specific materials and courses that explain their application in particular contexts. A major existing project on fractals can be used as an example[158]. There are two compelling reasons for the importance of such projects. The first is the wide applicability of complex systems concepts in science, engineering, medicine and management. The second is the great opportunity for engaging the public in exciting science with a natural relevance to daily life, and enhancing their support for ongoing and future research. Ultimately, the objective is to integrate complex systems concepts throughout the educational system.

There are various projects for describing specific complex systems[157,159-165], ranging from the earth to a single cell, which have been making substantial progress. Some of these focus more on generative simulation, others on representation of observational data. The greatest challenge is to merge these approaches and develop system descriptions that identify both the limits of observational and modeling strategies, and the opportunities they provide jointly for the description of complex systems. From this perspective, some of the most exciting advances are in representing human form in computer based animation[159-163] and particularly projecting a human being electronically: pattern recognition is performed on real-time video to obtain key information about dynamic facial expression and speech which is transmitted electronically to enable the animation of a realistic computer generated image that represents, in real time, the facial expression and speech of the person at a remote location[162]. Improvement in such a system is measured by the bandwidth that is necessary for the transmission, which reflects the inability to anticipate the system behavior from prior information. To advance this objective more broadly, developments in systematic approaches (quantitative languages, multiscale representations, information capture, visual interfaces) are necessary in conjunction with a set of complex systems models of: the earth, human civilization, the evolutionary history of life, a city, a person, an animal's developing embryo, a cell and an engineered system. For example, current computer based tools are largely limited to separated procedural languages (broadly defined) and databases. A more effective approach may be to develop quantitative descriptive languages based on lexical databases that merge the strength of human language for description with computer capabilities for manipulating and visually representing quantitative attributes[166]. Such extensible quantitative languages are a natural bridge between quantitative mathematics, physics, and engineering languages and qualitative lexicons which dominate description in biology, psychology and social sciences. They would facilitate describing structure, dynamics, relationships and functions better than, for example, graphical extensions of procedural languages[167]. This and other core complex systems approaches should be used in the description of a set of key complex systems under a coordinating umbrella. For each system an intensive collection of information would feed a system representation whose development would be the subject and outcome of the project. For example, in order to develop a representation of a human being, there must be intensive collection of bio-psycho-social information about the person. This could include multi-sensor monitoring of the person's physical (motion), psycho-social (speech, eye-motion), physiological (heart rate) and biochemical (food and waste composition, blood chemistry) activity over a long period of time, with additional periodic biological imaging and psychological testing. Virtual world animation would be used to represent both the person and his/her environment. Models of biological and psychological function representing behavioral patterns would be incorporated and evaluated. Detailed studies of a particular individual along with comparative studies of several individuals would be made to determine both what is common and what is different. As novel relevant convergent technologies becomes available that would affect human performance or affect our ability to model human behavior they can be incorporated into this study and evaluated. Similar projects would animate representations of the earth, life on earth, human civilization, a city, an animal's developing embryo, a cell and an engineered system, as suggested above. Each such project is both a practical application and a direct test of the limits of our insight, knowledge and capabilities. Success of the projects are guaranteed because their ultimate objective is to inform us about these limits.

The dramatic failures in large scale engineering projects, such as the Advanced Automation System(AAS) which was originally planned to modernize air traffic control should be addressed by complex systems research. The AAS is possibly the largest engineering project to be abandoned. It is estimated that several billion dollars were spent on this project[17]. Moreover, cost overruns and delays in modernization continue in sequel projects[17]. One approach to solving this problem, simplifying the task definition, cannot serve when the task is truly complex, as it appears to be in this context. Instead, a major experiment should be carried out to evaluate implementation of an evolutionary strategy for large scale engineering. In this approach, the actual air traffic control system would become an evolving system, including all elements of the system, hardware, software, the air traffic controllers, the designers and manufacturers of the software and hardware. The system context would be changed to enable incremental changes in various parts of the system, and an evolutionary perspective on population change. The major obstacle to any change in the air traffic control system is the concern for safety of airplanes, since the existing system, while not ideally functioning, is well tested. The key to enabling change in this system is to introduce redundancy that enables security while allowing change. For example, in the central case of changes in the air traffic control stations, the evolutionary process would use “trainers” that consist of doubled air traffic control stations, where one has override capability over the other. In this case, rather than an experienced and inexperienced controller, the two stations are formed of a conventional and a modified station. The modified station can incorporate changes in software or hardware. Testing can go on as part of operations, without creating undue risks. With a large number of trainers, various tests can be performed simultaneously and for a large number of conditions. As a particular system modification becomes more extensively tested, and found both effective and reliable, it can be propagated to other trainers even though testing would continue for extended periods of time. While the cost of populating multiple trainers would appear to be high, the alternatives have already been demonstrated to be both expensive and unsuccessful. The analogy with paired chromosomes in DNA can be seen to reflect the same redundancy/robustness design principle. This brief paragraph is not sufficient to explain the full evolutionary context, but it does resolve the key issue of safety and points out the opening that this provides for change. Such evolutionary processes are also being considered for guiding other large scale engineering modernization programs[11].

Conclusions

The excitement that is currently felt in the study of complex systems arises not from a complete set of answers but rather from the appearance of a new set of questions. These questions differ from the conventional approaches to science and technology and provide an opportunity to make major advances in our understanding and in applications.

The importance of complex systems ideas in technology begins through the recognition that novel technologies promise to enable us to create ever more complex systems. Even graphics oriented languages like OpenGL are based on a procedural approach to drawing objects rather than representing them. Moreover, the conventional boundary between technology and the human beings that use them is not a useful approach to thinking about complex systems of human beings and technology. For example, computers as computational tools have given way to information technology as an active interface between human beings that are working in collaboration. This is now changing again to the recognition that human beings and information technology are working together as an integrated system.

More generally, complex systems provides a framework in which we can understand how the planning, design, engineering and control over simple systems gives way to new approaches that enable such systems to arise and be understood with limited or indirect planning or control. Moreover, it provides a way to better understand and intervene (using technology) in complex biological and social systems.

References:

1) Y. Bar-Yam, ed., Unifying Themes in Complex Systems: Proceedings of the International Conference on Complex Systems, (Perseus Press, 2000)
2) Y. Bar-Yam and A. Minai, eds., Unifying Themes in Complex Systems II: Proceedings of the 2nd International Conference on Complex Systems, (Perseus Press, 2002)
3) R. Gallagher and T. Appenzeller, Beyond Reductionism, Science 284, 79 (1999)
4) R. F. Service, COMPLEX SYSTEMS: Exploring the Systems of Life, Science 284, 80 (1999)
5) D. Normile, COMPLEX SYSTEMS: Building Working Cells 'in Silico' Science 284, 80 (1999)
6) G. Weng, U.S. Bhalla, R. Iyengar, Complexity in Biological Signaling Systems, Science 284, 92 (1999)
7) L. H. Hartwell, J. J.Hopfield, S. Leibler and A. W. Murray, From molecular to modular cell biology. Nature 402 supplement. 6761: C47-C52 (1999)
8) D. S. Alberts, J. J. Garstka, F. P. Stein, Network Centric Warfare, DoD C4ISR Cooperative Research Program (1999)
9) Joint Vision 2010: http://www.dtic.mil/jv2010/jv2010.pdf
10) Future Combat Systems: http://www.darpa.mil/fcs/
11) Y. Bar-Yam, Multiscale Representation Phase I, Final Report to Chief of Naval Operations Strategic Studies Group (2001)
12) 1997 Strategic Assessment, Institute for National Strategic Studies, National Defense University, http://www.ndu.edu/inss/sa97/sa97exe.html (1997)
13) D. Priest, Special Forces May Play Key Role, Washington Post, (Sept. 14, 2001)
14) J. R. Cares, New Perspectives on Conventional Military Force and the War On Terrorism, Washington DC, Sponsored by Joint Chiefs of Staff, April (2002)
15) Y. Bar-Yam, Dynamics of Complex Systems (Perseus, 1997)
16) Y. Bar-Yam, General Features of Complex Systems, UNESCO Encyclopaedia of Life Support Systems (in press)
17) U.S. House Committee on Transportation and Infrastructure, FAA Criticized For Continued Delays In Modernization Of Air Traffic Control System, (March 14, 2001)
18) http://www.wired.com/news/technology/0,1282,5062,00.html, http://www.wired.com/news/topstories/0,1287,8415,00.html
19) To Err Is Human: Building a Safer Health System, Institute of Medicine (2000)

20) Doing What Counts for Patient Safety:Federal Actions to Reduce Medical Errors and Their Impact, Report of the Quality Interagency Coordination Task Force (QuIC) to the President, (February, 2000)
21) Rezulin To Be Withdrawn From The Market, U.S. Department of Health and Human Services, P00-8, (March 21, 2000)
22) D. Willman, \`Fast Track´ Drug to Treat Diabetes Tied to 33 Deaths, Los Angeles Times, Wednesday, (December 6, 1998)
23) The CHAOS Report, The Standish Group (1994)
24) A. S. Perelson and F. W. Wiegel, Some design principles for immune system recognition. Complexity 4, 29-37(1999)
25) A. J. Noest, Designing Lymphocyte Functional Structure for Optimal Signal Detection: Voilà, T cells, Journal of Theoretical Biology, 207, 2, 195-216, (2000).
26) I. Cohen and L. A. Segel, eds., Design Principles of the immune system and other distributed autonomous systems, (Oxford University Press, 2001)
27) D. M. Pierre, D. Goldman, Y. Bar-Yam and A. S. Perelson, Somatic Evolution in the Immune System: The Need for Germinal Centers for Efficient Affinity Maturation, J. Theor. Biol. 186, 159-171 (1997)
28) J. A. Anderson and E. Rosenfeld eds. Neurocomputing (MIT Press, Cambridge, 1988).
29) C. M. Bishop, Neural Networks for Pattern Recognition. Oxford University Press (1995)
30) E. R. Kandel, J. H. Schwartz and T. M. Jessell, eds., Principles of Neural Science 4th ed., (McGraw-Hill, 2000)
31) G. S. Triantafyllou and M. S. Triantafyllou, An efficient swimming machine, Scientific American, 272, 64-70 (1995).
32) M. Golubitsky , I. Stewart, P.L. Buono, and J.J. Collins, Symmetry in locomotor central pattern generators and animal gaits, Nature 401, 6754, 693-695 (Oct 14 1999)
33) L. A. Stein, Challenging the computational metaphor: Implications for how we think, Cybernetics and Systems 30 (6):473-507, (1999)
34) V. Paxson. "End-To-End Routing Behavior in the Internet". In Proceedings of the ACM SIGCOMM '96 Conference on Communications, Architectures and Protocols, (1996)
35) J.O. Kephart, A Biologically Inspired Immune System for Computers, in R.A. Brooks, P. Maes, (Ed), Artificial Life IV, Proceedings of the Fourth International Workshop on the Synthesis and Simulation of Living Systems, 130-139 (1994)
36) S. Forrest, S. A. Hofmeyr and A. Somayaji, Computer Immunology, Communications of the ACM, vol. 40, pp. 88-96, (1997)
37) J. O. Kephart, G. B. Sorkin, D. M. Chess and S. R. White, Fighting Computer Viruses: Biological metaphors offer insight into many aspects of computer viruses and can inspire defenses against them, Scientific American, (November, 1997).
38) L. A. Goldberg, P. W. Goldberg, C. A. Phillips and G. B. Sorkin, Constructing computer virus phylogenies, Journal of Algorithms, 26 (1): 188-208 (1998)
39) Learning and the Brain, National Institute of Mental Health, NIH, http://www.edupr.com/brain4.html
40) D. A. Norman and S. Draper, Eds. User Centered System Design: New Perspectives in Human-Computer Interaction. Hillsdale, NJ: Erlbaum. (1986).

41) J. Nielsen, Usability Engineering (Academic Press. Boston, 1993).

42) E. Hutchins, Cognition in the Wild (MIT Press, Cambridge, 1995).

43) The Aging Mind: Opportunities in Cognitive Research, P. C. Stern and L. L. Carstensen, Eds, (National Academies, 2000)

44) M. P. Lawton, Environment and aging. (Brooks/Cole, Monterrey, 1981).

45) A. J. Mandell , & M. F. Schlesinger, Lost choices: Parallelism and topo entropy decrements in neurobiological aging in The ubiquity of chaos, edited by S. Krasner, 35-46 (Amer Assoc Adv of Science, Washington, DC, 1990)

46) A. Davidson, M. H. Teicher and Y. Bar-Yam, The Role of Environmental Complexity in the Well Being of the Elderly, Complexity and Chaos in Nursing, 3, 5 (1997)

47) Partnership for Development: Proposed Actions for the World Bank, (World Bank, May 1998)

48) J. D. Wolfenson, A Proposal for a Comprehensive Development Framework (A Discussion Draft) (World Bank, January 21, 1999)

49) Biocomplexity in the Environment, NSF-02-010

50) J. D. Sterman, Business Dynamics: Systems Thinking and Modeling for a Complex World (Irwin Professional, 2000)

51) R. D. Stacey, Complexity and Creativity in Organizations, (Berrett-Koehler, 1996); Complex Responsive Processes in Organizations (Routledge, 2001)

52) J.C. Herz, The Allure of Chaos, The Industry Standard, (Jun 25, 2001) http://www.thestandard.com/article/0,1902,27309,00.html

53) P. Horn, Autonomic Computing, IBM (2001)

54) R. L. Strausberg and M. J. F. Austin, Functional genomics: technological challenges and opportunities, Physiological Genomics 1:25-32 (1999)

55) Biocomplexity initiative: http://www.nsf.gov/pubs/1999/nsf9960/nsf9960.htm; http://www.nsf.gov/pubs/2001/nsf0134/nsf0134.htm; http://www.nsf.gov/pubs/2002/nsf02010/nsf02010.html

56) Complex Biological Systems Initiative, National Institute of General Medical Science, NIH, http://www.nigms.nih.gov/funding/complex_systems.html

57) Joint DMS/NIGMS Initiative to Support Research Grants in Mathematical Biology, http://www.nsf.gov/cgi-bin/getpub?nsf01128

58) B. Zimmerman, P. Plsek and C. Lindberg, Edgeware: insights from complexity science for health care leaders, (VHA, 1998)

59) Embracing Complexity, Center for Business Innovation, Ernst and Young, Vol. 1-5, 1996-2000. http://www.cbi.cgey.com/research/current-work/biology-and-business/complex-adaptive-systems-research.html

60) Biosgroup, http://www.biosgroup.com/

61) J. Gleick, Chaos: Making a New Science (Penguin: New York, 1987)

62) R. Lewin, Complexity: Life at the Edge of Chaos (Macmillan: New York, 1992).

63) M. M. Waldrop, Complexity: The Emerging Science at the Edge of Order and Chaos (Simon & Schuster: New York, 1992).

64) M. Gell-Mann, The Quark and the Jaguar, (W H Freeman & Co., 1994)

65) J. L. Casti, Complexification: Explaining a Paradoxical World through the Science of Surprise (HarperCollins: New York, 1994).
66) B. Goodwin, How the Leopard Changed its Spots: The Evolution of Complexity (Charles Scribner's Sons, New York, 1994).
67) S. A. Kauffman, At Home in the Universe (Oxford University Press: New York, 1995).
68) . H. Holland, Hidden Order: How Adaptation Builds Complexity (Helix Books, Addison-Wesley: Reading, Mass., 1995).
69) P. Coveney and R. Highfield, Frontiers of Complexity: The Search for Order in a Chaotic World (Fawcett Columbine: New York, 1995).
70) P. Bak, How Nature Works: The Science of Self-Organized Criticality (Copernicus, Springer-Verlag: New York, 1996).
71) P. Cvitanovic, ed. Universality in Chaos: A Reprint Selection, 2d ed. (Adam Hilger: Bristol, 1989)
72) R. L. Devaney, A First Course in Chaotic Dynamical Systems: Theory and Experiment (Addison-Wesley: Reading, Mass., 1992).
73) R. L. Devaney, Introduction to Chaotic Dynamical Systems, 2d ed. (Addison-Wesley, Reading, Mass., 1989).
74) S. H. Strogatz, Nonlinear Dynamics and Chaos. With Applications to Physics, Biology, Chemistry, and Engineering (Addison-Wesley: Reading, 1994).
75) E. Ott, Chaos in Dynamical Systems (Cambridge University Press, Cambridge, 1993).
76) W. R. Ashby, An Introduction to Cybernetics, (Chapman and Hall, London, 1957)
77) E. H. Simpson, The Interpretation of Interaction in Contingency Tables, Journal of the Royal Statistical Society, Ser. B, 13, 238-241 (1951)
78) K. J. Arrow, Social choice and individual values, (Wiley, 1963).
79) D. A. Meyer and T. A. Brown, Statistical mechanics of voting, Phys. Rev. Lett. 81, 1718-1721 (1998)
80) A. Turing, The chemical basis of morphogenesis, Phil. Trans. R. Soc. Lond. B237: 37-72 (1952)
81) H. Meinhardt, The Algorithmic Beauty of Sea Shell Patterns, (Springer-Verlag, New York, 1994)
82) J. D. Murray, Mathematical Biology, (Springer-Verlag, New York, 1989)
83) H. F. Nijhout, The development and evolution of butterfly wing patterns, (Smithsonian Institution Press, 1992)
84) L. A. Segel, Modeling Dynamic Phenomena in Molecular and Cellular Biology, (Cambridge University Press, Cambridge, (1984)
85) P. Ball, The Self-made Tapestry: Pattern Formation in Nature, (Oxford Univ. Press., 1999)
86) A. J. Bray, Advances in Physics 43, 357 (1994).
87) P. Bak, C. Tang, and K. Wiesenfeld, Self-organized criticality - an explanation of 1/f noise, Phys. Rev. Lett. 59, 381 (1987)
88) M. Kardar, G. Parisi, and Y.-C. Zhang, Dynamic scaling of growing interfaces, Phys. Rev. Lett. 56, 889 (1986).

89) S. Kirkpatrik and D. Sherrington, Infinite-ranged model of spin-glasses, Phys. Rev. B 17, 4384 (1978).
90) S. Kauffman, Metabolic Stability and Epigenesis in Randomly Constructed Genetic Nets, J. Theor. Biol. 22, 437 (1969)
91) C. E. Shannon, "A Mathematical Theory of Communication," in Bell Systems Technical Journal, July and October 1948; reprinted in C. E. Shannon and W. Weaver The Mathematical Theory of Communication (University of Illinois Press, Urbana, 1963).
92) K. G. Wilson, The Renormalization-Group and Critical Phenomena, Reviews of Modern Physics 55 (3): 583-600 (1983)
93) C. Darwin, On the Origin of Species (By Means of Natural Selection) (a facsimile of the first edition, 1859) (Harvard University Press: Cambridge, 1964).
94) J. H. Holland, Adaptation in Natural and Artificial Systems, 2d ed. (MIT Press: Cambridge, 1992)
95) S. A. Kauffman, The Origins of Order: Self Organization and Selection in Evolution (Oxford University Press, New York, 1993).
96) R. N. Brandon and R. M. Burian, eds. Genes, Organisms, Populations: Controversies Over the Units of Selection (MIT Press, Cambridge, 1984).
97) Y. Bar-Yam, Formalizing the Gene-Centered View of Evolution, Advances in Complex Systems, 2, 277-281 (2000)
98) H. Sayama, L. Kaufman and Y. Bar-Yam: Symmetry breaking and coarsening in spatially distributed evolutionary processes including sexual reproduction and disruptive selection, Phys. Rev. E 62, 7065 (2000)
99) E. Sober and D. S. Wilson, Unto Others (Harvard Univ. Press, Cambridge, 1999)
100) R. M. Axelrod, The Evolution of Cooperation (Basic Books: New York, 1984).
101) R. Lewontin, The Triple Helix : Gene, Organism, and Environment (Harvard Univ. Press, Cambridge, 2000)
102) William Day, Genesis on Planet Earth: The Search for Life's Beginning, 2d ed. (Yale University Press: New Haven, 1984).
103) Melanie Mitchell, An Introduction to Genetic Algorithms (Bradford, MIT Press: Cambridge, 1996).
104) L J Fogel, A J Owens and M J Walsh, Artificial Intelligence through Simulated Evolution, (Wiley, New York, 1966).
105) D. Herschlag and T. R. Cech, DNA cleavage catalysed by the ribozyme from Tetrahymena. Nature, 344, 405-410. (1990)
106) A. A. Beaudry and G. F. Joyce, Directed evolution of an RNA enzyme, Science, 257, 635-641 (1992)
107) J. W. Szostak, In vitro selection and directed evolution, Harvey Lectures 93:95-118 (John Wiley & Sons, 1999)
108) H. A. Simon, The Sciences of the Artificial, 3rd ed. (MIT Press, Cambridge, 1998).
109) J. von Neumann and O. Morgenstern, Theory of Games and Economic Behavior. (Princeton University Press, Princeton, 1944)
110) J. Maynard Smith, Evolution and the Theory of Games. (Cambridge University Press, Cambridge, 1982)

111) D. Fudenberg and J. Tirole, Game Theory (MIT Press, Cambridge, 1991)
112) R. J. Aumann and S. Hart, eds. Handbook of Game Theory with Economic Applications, Vol. 1. (North-Holland, Amsterdam, 1992); Vol. 2. (North-Holland, Amsterdam, 1994)
113) 2001 National Transportation Atlas, Transportation Networks, Geographic Information Services, http://www.bts.gov/gis/
114) A. Maritan, F. Colaiori, A. Flammini, M. Cieplak and J. Banavar, Universality classes of optimal channel networks. Science 272, 984–986 (1996)
115) J. R. Banavar, A. Maritan, and A. Rinaldo, Size and form in efficient transportation networks. Nature 399, 130–132 (1999);
116) P. S. Dodds and D. H. Rothman, Scaling, Universality, and Geomorphology. Annu. Rev. Earth Planet. Sci. 28: 571-610 (2000).
117) S. Wasserman and K. Faust, Social Network Analysis (Cambridge University Press, Cambridge, 1994).
118) B. Cheswick and H. Burch, Internet Mapping Project, http://www.cs.bell-labs.com/who/ches/map/
119) K. Claffy, T. E. Monk & D. McRobb. Internet tomography. Nature [online] (7 Jan. 99) http://helix.nature.com/webmatters/tomog/tomog.html (1999); http://www.caida.org/
120) E. W. Zegura, K. L. Calvert and M. J. Donahoo, A quantitative comparison of graph-based models for internet topology. IEEE/ACM Trans. Network. 5, 770–787 (1997).
121) S. Lawrence and C. L. Giles, Accessibility of information on the web. Nature 400, 107–109 (1999)
122) B. A. Huberman, P. Pirolli, J. Pitkow and R. M. Lukose, Science 280, 95–97 (1998);
123) B. A. Huberman and R. M. Lukose, Science 277, 535–538 (1997).
124) R. J. Williams and N. D. Martinez, Simple rules yield complex food webs. Nature 404, 180–183 (2000).
125) P. Erdös & A. Rényi, On the evolution of random graphs. Publ. Math. Inst. Hung. Acad. Sci. 5, 17–60 (1960).
126) B. Bollobás, Random Graphs (Academic, London, 1985).
127) S. Milgram, The Small-World Problem. Psychol. Today 2, 60–67 (1967).
128) S. Milgram, The Small World Problem. In: S. Milgram, J. Sabini, and M. Silver (eds.): The Individual in a Social World: Essays and Experiments. 2nd Edition. (McGraw Hill., New York, 1992)
129) D. J. Watts, & S. H. Strogatz, Collective dynamics of ‘small-world’ networks. Nature 393, 440–442 (1998).
130) M. Barthélémy & L. A. N. Amaral, Small-world networks: evidence for a crossover picture. Phys. Rev. Lett. 82, 3180–3183 (1999)
131) D. J. Watts, Small Worlds, Princeton Univ Press, Princeton (1999)
132) V. Latora and M. Marchiori, Efficient Behavior of Small-World Networks, Phys. Rev. Lett. 87, 198701 (2001)
133) A.-L. Barabási & R. Albert, Emergence of scaling in random networks. Science 286, 509–511 (1999)

134) R. Albert, H. Jeong, & A.-L. Barabási, Diameter of the World-Wide Web. Nature 401, 130–131 (1999)

135) B. A. Huberman & L. A. Adamic, Growth dynamics of the World-Wide Web. Nature 401, 131 (1999).

136) M. Faloutsos, P. Faloutsos, and C. Faloutsos, "On power-law relationships of the Internet topology," in SIGCOMM'99, 1999. Comput. Commun. Rev. 29, 251–263 (1999)

137) R. Albert, H. Jeong and A-L. Barabási, Error and attack tolerance of complex networks, Nature, 406, 378-382 (2000)

138) H. Jeong, B. Tombor, R. Albert, Z. Oltvai and A.-L. Barabási, The large-scale organization of metabolic networks. Nature (2001)

139) A. Fersht, Structure and Mechanism in Protein Science: A Guide to Enzyme Catalysis and Protein Folding (W H Freeman & Co., 1999)

140) G. von Dassau, E. Meir, E. M Munro and G. M Odell, The Segment Polarity is a Robust Developmental Module, Nature, 406, 188 (2001)

141) An interview with Clay Easterly, Oak Ridge National Laboratory, OE Reports 169 (January, 1998)

142) Virtual Human, Science at the Interface Oak Ridge Review, 33, 8-11 (2000)

143) The Visible Human Project, National Library of Medicine, http://www.nlm.nih.gov/research/visible/visible_human.html

144) D. Quist, I. H. Chapela, Transgenic DNA introgressed into traditional maize landraces in Oaxaca, Mexico, Nature 414, 541 - 543 (29 Nov 2001)

145) A. L. Goldberger, D. R. Rigney and B. J. West, Chaos and fractals in human physiology. Sci. Amer. 262: 40-49 (1990)

146) L. A. Lipsitz, and A. L. Goldberger, Loss of “complexity” and aging. Journal of the American Medical Association, 267, 1806-1809 (1992)

147) Described by D. Clark, MIT Laboratory for Computer Science (2001)

148) Described by Autonomic Computing Group, IBM (2002)

149) G. Bush, By the President of the United States of America A Proclamation, Presidential Proclamation 6158 (1990)

150) J. B. Rowe, I. Toni, O. Josephs, R. S. J. Frackowiak, and R. E. Passingham, The prefrontal cortex: Response selection or maintenance within working memory? Science 288 (5471), 1656-1660 (JUN 2, 2000)

151) M. Schena, D. Shalon, R. W. Davis and P. O. Brown, Quantitative monitoring of gene-expression patterns with a complementary-DNA microarray, Science 270 (5235): 467-470 (1995)

152) S. Fuhrman, X. Wen, G. Michaels, and R. Somogyi, Genetic network inference. InterJournal, 104 (1998); and in Ref. 1, 201-207

153) E.N. Lorenz, Deterministic nonperiodic flow , J. Atmosph. Sci. 20, 130-141 (1963)

154) P. Bak and C. Tang, Earthquakes as a self-organized critical phenomenon, J. Geophys. Res., 94, 15, 635-637 (1989)

155) J. B. Rundle, D. L. Turcotte and W. Klein, Eds, Reduction and Predictability of Natural Disasters, (Perseus Press, 1996)

156) S. A. Levin, Fragile Dominion, (Perseus, Cambridge, 1999)

157) Ecosystems and Global Change, NOAA National Data Centers, NGDC http://www.ngdc.noaa.gov/seg/eco/eco_sci.shtml

158) S. V. Buldyrev, M. J. Erickson, P. Garik, P. Hickman, L. S. Shore, H. E. Stanley, E. F. Taylor, and P. A. Trunfio, "Doing Science" by Learning about Fractals (Center for Polymer Science Working Paper, Boston University).

159) TRANSIMS 2.1 Documentation, Los Alamos National Laboratory (2002)

160) N. I. Badler, R. Bindiganavale, J. Bourne, J. Allbeck, J. Shi and M. Palmer, Real Time Virtual Humans, Proceedings of International Conference on Digital Media Futures British Computer Society, Bradford, UK, (1999)

161) P. Kalra, N. Magnenat Thalmann, L. Moccozet, G. Sannier, A. Aubel, D. Thalmann, "RealTime Animation of Realistic Virtual Humans", Computer Graphics and Applications, Vol. 18, No. 5, 1988, pp. 42-56

162) T. Goto, S. Kshirsagar and N. Magnenat-Thalmann, "Automatic Face Cloning and Animation", IEEE Signal Processing Magazine May 2001, Vo. 18, No. 3, pp 17-25

163) Virtual Worlds: Synthetic Universes, Digital Life and Complexity, Ed. J.-C. Heudin (Perseus Books, Reading, 1999)

164) J. Schaff, C. Fink, B. Slepchenko, J. Carson and L. Loew, "A General Computational Framework for Modeling Cellular Structure and Function", Biophys. J. 73:1135-1146 (1997)

165) M. Tomita, K. Hashimoto, K. Takahashi, T. Shimizu, Y. Matsuzaki, F. Miyoshi, K. Saito, S. Tanida, K. Yugi, J. C. Venter, C. Hutchison, E-CELL: Software environment for whole cell simulation, Bioinformatics, 15, 316-317 (1999)

166) M. Smith, W. Gelbart and Y. Bar-Yam, Quantitative Languages for Complex Systems Applied to Biological Structure, in Nonlinear Dynamics in the Life and Social Sciences, W. Sulis and I. Trofimova, eds., NATO Science Series A/320, 65-71, (IOS Press, Amsterdam, 2001)

167) http://www.sgi.com/software/opengl/