Complex Engineered, Organizational and Natural Systems

Issues Underlying the Complexity of Systems and Fundamental Research Needed To Address These Issues*

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ABSTRACT

This paper describes an effort to determine the rationale and content for a research agenda in complex systems. This effort included a workshop conducted with 50 thought leaders in complex engineered, organizational, and natural systems. The results of this workshop were subsequently presented to seven groups in academia and industry across the United States. In this way, additional comments, suggestions, and insights were gained from roughly 200 participants in these presentations. The objectives of these eight events were to understand the underlying issues that cause us to perceive a system to be complex, and formulate a set of fundamental research questions whose pursuit would advance abilities to address these issues. © 2007 Wiley Periodicals, Inc. Syst Eng: 260–271, 2007

Key words: complexity; complex systems; systems of systems; architectures; fundamental limits

1. INTRODUCTION

The United States is faced with a variety of major challenges. The healthcare delivery system is believed to be unsustainable [Institute of Medicine, 2001; Na-

tional Academies, 2006]. The nation's infrastructure is projected to require enormous investments over the coming decades [Committee on Critical Infrastructure Protection, 1997]. Environmental challenges range from global warming to depletion of water resources. Security challenges include threats to air travel, sea cargo, and food and water supply. The economic activities associated with these issues account for well over 25% of the Gross Domestic Product.

There are also broader economic challenges. Thomas Friedman's best seller, *The World Is Flat* [2005], provided a clarion call to the business and technology communities. Several countries, particularly in Asia, have caught up with the United States in terms of various indices of innovation and are producing huge numbers of talented college graduates, particularly in engineering. This challenges both industry in terms of how to best compete and academia in terms of educating people with competitive knowledge and skills.

The National Academy of Engineering has concluded that engineers in the U.S. need a more broadly-based education that enables them to understand the complexity of systems within which their technologies are deployed [NAE, 2004]. This need conflicts with the great emphasis over the past few decades on intense specialization in engineering science. The ability to understand and address complex systems requires consideration of many phenomena that are not inherently considered to be engineering phenomena [Ottino, 2004]. Traditional engineering science communities are likely to find it very difficult to adapt to these new educational needs.

These systems—healthcare, infrastructure, environment, security, and the economy—are complex systems. They involve large numbers of interacting elements. There are many attributes of interest and many stakeholders, who often have differing objectives and needs. With these many stakeholders acting and reacting, the response of these systems can be unpredictable with phenomena emerging that could not have been anticipated.

Of course, complex systems are not new. We have researched, developed, and applied systems engineering methods and tools for many decades. There is renewed interest and emphasis in this field as we have learned that deeper and deeper emphasis on engineering science, despite its importance, is not sufficient for addressing large-scale complex systems. We need a balance of reductionism and holism. We also need a broad enterprise perspective that will require integration of behavioral, social, and life sciences, as well as management, to address systems of increasing scale and complexity.

The current growth of research and education programs in the following areas also provides evidence of changing perspectives:

- Engineering Systems: The Council on Engineering Systems Universities includes many of the top engineering institutions in the world. CESUN (www.cesun.org) was formed to provide a forum for those who are building and managing transdisciplinary programs to address complex system. Several of the leaders of CESUN were instrumental in the gestation and conduct of the work reported here.
- Services Sciences: This set of initiatives is exemplified by IBM's focus on Services Sciences, Management, and Engineering. Particular attention is paid to how providers and clients "co-create" value in service systems—see, for instance, Normann [2001]. A recent special issue of the *Communications of the ACM* provides an overview of this emerging field [ACM, 2006].
- Systems Biology: Several new Institutes for Systems Biology have emerged at various leading universities. These initiatives focus on living systems as wholes within which biological components and systems interact to enable phenomena at levels above the functions of these elements [Konopka, 2006].

The formation and prominence of these programs reflect the recognized need to understand the whole as well as the parts.

The National Science Foundation (NSF) has recognized the need to support fundamental research that will help address national challenges such as described above. In pursuit of this goal, the Directorate for Engineering created a program, Emerging Frontiers in Research and Innovation (EFRI) (www.nsf.gov/div/index.jsp?div=EFRI). This is a key element of the Foundation's response to the American Competitiveness Initiative, which is intended to double the NSF budget over the next ten years.

This paper describes an effort to determine the rationale and content for a potential EFRI solicitation in complex systems. This effort included a workshop conducted in September 2006 with 50 thought leaders in complex engineered, organizational, and natural systems. The results of this workshop were subsequently presented in November and December 2006 to seven groups in academia and industry across the United States. In this way, additional comments, suggestions, and insights were gained from roughly 200 participants in these presentations.

The objectives of these eight events were to understand the underlying issues that cause us to perceive a system to be complex, and formulate a set of fundamental research questions whose pursuit would be appropriate for NSF to sponsor given its charter to support fundamental research. The next section outlines the methodological structure of this overall effort, including the design of the workshop. Results of the workshop are then discussed, followed by recommendations to the Foundation.

2. METHODOLOGY

This effort began with the formation of an external Planning Committee and an internal NSF Working Group. These groups formulated the objectives and design of the Workshop on Complex Engineered, Organizational, and Natural Systems. The workshop design is discussed in the next subsection.

The workshop was held in Washington, DC on September 28–29, 2006. Each of three working groups produced two sets of outputs: (1) a list of issues underlying the complexity of systems and (2) a list of fundamental research topics that should be pursued to address these issues. The working group participants as a whole produced an initial set of conclusions and recommendations.

Subsequent to the workshop, the working group reports were converted from presentations to spreadsheets, and analyzed to yield 41 issues and 51 topics. These entries were categorized and sorted, and then subcategorized and resorted. The results were sent to the external Planning Committee for review and comment. The results were revised based on committee members' comments and suggestions.

The results—in terms of issues, topics, conclusions, and recommendations—were then incorporated into a PowerPoint presentation that was delivered at the following seven venues during November and December 2006:

- Carnegie Mellon University (CESUN Annual Meeting)
- Georgia Tech (Tennenbaum Institute)
- MIT (Engineering Systems Division)
- University of Southern California (Department of Industrial & Systems Engineering)
- IBM (Almaden Research Center)
- Georgia Tech (School of Civil and Environmental Engineering)
- George Mason University (Department of Systems Engineering and Operations Research)

The comments and suggestions from the audiences attending these presentations were incorporated into the presentation and are reflected in this paper in terms of a greatly expanded set of conclusions and recommendations.

3. WORKSHOP DESIGN

The workshop was designed to bring together thought leaders in order to help formulate a research agenda on complex systems. We knew from our planning efforts that these deliberations would be more productive if we considered several complex systems domains. The domains chosen are discussed below.

3.1. Workshop Agenda

The workshop agenda covered two days—September 28–29, 2006. The first day began with a charge to participants by Mario Rotea, the NSF Program Manager for this initiative, followed by the presentations summarized below. Over the course of the two days, Domain Problem Working Groups met three times, each time followed by a plenary report on their findings. The workshop concluded with plenary drafting of overall conclusions and discussion of next steps for this initiative.

Richard Buckius, NSF Assistant Director for Engineering, followed the charge to participants. He focused on the American Competitiveness Initiative, which is intended to support investments by NSF, the Department of Energy, and the National Institute for Standards and Technology to double, over ten years, the federal investment in key agencies that support basic research in physical sciences and engineering. He also discussed how these new resources would increase investigators' chances of success in gaining support from NSF, in the context of the Foundation's growing support for multi-investigator awards. This set the stage for presenting the new organization of the Directorate for Engineering, highlighting the program on Emerging Frontiers in Research and Innovation (EFRI). The research agenda reported here is directed at this program.

William Rouse then provided a broad overview of "Complexity and Complex Systems". A range of definitions of complexity were discussed [Carlson and Doyle, 2002; Gell-Mann, 1995; NIST, 2004], as were alternative characterizations of complex systems. He summarized various domain-specific studies of complexity, including failure diagnosis [Rouse and Rouse, 1979], control of large-scale hierarchical systems [Henneman and Rouse, 1986], and disease control [Rouse, 2000]. Alternative views of complex systems included hierarchical mappings, state equations, nonlinear

mechanisms, and autonomous agents [Rouse, 2003]. The approach, focus, and spanning issues associated with these views were discussed.

Rouse also presented a brief review of international research in complex systems. He highlighted 15 research institutes, 5 portals, and 3 professional journals, as well as other academic organizations and professional associations whose portfolios of research and education activities include complexity and complex systems. This provided the participants at the workshop with a sense of the richness of the "waterfront" in this area.

On the second day of the workshop, John Doyle's presentation on "What Is Complexity?" began by outlining the nature of the confusion surrounding the topic [Carlson and Doyle, 2002]. He discussed background from biology, technology, and mathematics. Contrasting simplicity and complexity, he considered unpredictability and emergence. However, primary emphasis was given to "organized complexity" which requires highly organized interactions by design or evolution, and can be contrasted with emergence. The notion that such systems are robust yet fragile was elaborated [Doyle et al., 2005]. Doyle argued that architecture is a central challenge to understanding and designing systems with organized complexity.

3.2. Domain Problems

Three domain problems were employed to assess the impact of context on the working groups' conclusions. The choice was limited to three problems to keep the workshop manageable.

- Infrastructure & Transportation—Proactive monitoring, discovery and prevention of abnormal (catastrophic) behavior in critical infrastructure systems.
- Health Care Delivery—Transformation of the overall healthcare delivery system, across all providers, suppliers, insurers, and so on, to foster and sustain value-based competition.
- Bacteria Level Design—Design of a control circuit for bacteria that can be inserted into a bacterium and that will modify its behavior so that the bacterium can be used to deliver a drug to a specific area in an organism.

The choice of these three problems was determined by a desire to have one problem that emphasized engineering (infrastructure), one that emphasized organization (health care) and one that focused on a natural system at the micro or nano level (bacteria design). The

complete descriptions of the domain problems can be found in the full report of this initiative [Rouse, 2007].

It is important to note that these domains were examined to prompt discussion of the characteristics of complexity and research needed to address these characteristics. We did our best to inhibit the working groups from trying to "solve" the associated problems in the few hours they had to discuss them. The facilitators of the three groups were instructed to keep the discussion focused on issues and topics rather than the natural tendency to design solutions.

3.3. Workshop Participants

Other than NSF program managers, over 70 potential participants were invited. These invitees were complexity experts, domain experts, or managers from other government agencies, e.g., DARPA, other DoD, and NASA. All invitees were approved by the internal NSF Working Group.

There were roughly 50 participants at the September 2006 workshop. NSF participation included over 20 program managers and senior managers from all Divisions within the Directorate for Engineering. There were 19 participants from 11 universities, as well as two from the Air Force Office of Scientific Research, one from the National Academy of Engineering, and one from IBM. As noted earlier, the seven presentations following the workshops included roughly 200 participants.

4. WORKSHOP RESULTS

This section summarizes the results of the workshop in terms of issues underlying complexity and fundamental research needed to address these issues. This material was presented in the seven followup presentations noted earlier. However, the audiences for these presentations were not asked to suggest changes to the workshop results. Instead, as the next main section indicates, they were asked to provide comments and suggestions on the interpretation and implications of these results.

4.1. Issues Underlying Complexity

Table I shows how the three working groups aligned with the seven categories of issues identified. Clearly, at least from the perspectives of the experts in each working group, there are important differences among domains. For example, the bacteria level design discussions focused more on complexity due to interactions at that level, while the healthcare delivery discussions, as well as those in bacteria level design, argued that complexity is highly related to the context of the domain. Nevertheless, empty (white) cells in this table do

Table I. Issues vs. Domains

	Infrastructure & Transportation	Healthcare Delivery	Bacteria Level Design
Context		■	■
Modeling	■	■	■
Interactions			■
Multi-Stakeholder, Multi-Objective	■	■	■
Learning & Adaptation	■	■	■
Information & Control	■	■	■
Other		■	

not reflect a lack of interest of some groups for several issues—as plenary discussions showed, to a great extent, the issues simply did not arise during their deliberations. Given the differences among the domains, it was natural that some issues received more attention than others.

In general, however, there was a strong sense that complexity is related to the context of system definition, design, development, deployment, and operations. Broadly, this includes globalization and competitiveness, as well as issues such as sustainability. More specifically, however, context relates to the operational environments of the associated systems. The functioning of systems can depend on context, e.g., we function differently when sleeping than when awake and active.

Context also concerns how system boundaries are framed. Some participants argued for "internalizing the externalities." Others were concerned that system boundaries not exceed one's span of authority. Of course, these two arguments are not completely in conflict. However, there is the problem of defining boundaries so broadly that virtually everything is included. One person commented that this results in there being only one complex systems problem—life. In contrast, it was also argued that characterizing boundaries is less an issue than understanding the environment within which a system operates.

There was also discussion of systems and issues that are difficult to bound, for example, the Internet, ant colonies, and the economy. It was suggested that diffuse boundaries that are continually evolving tend to increase the perceived complexity of systems. Perhaps perceived complexity relates to the extent that aspects of a system are inherently hidden and unobservable.

There were many observations about the modeling of complex systems, as later conclusions illustrate. This included discussion of attributes such as drivers, limiters, and effectors, as well as the need to consider multiple levels and multiple time scales of system operations. There was considerable discussion of networks, network hierarchies, and architectures that enable representation of complex systems across levels and time scales.

It was frequently argued that complexity is due to the number and nature of interactions within a system. To comprehend a complex system, we need to understand how all the parts work together. This can include the impact of redundancy, where the system may compensate for failures until the point is reached that cascading failure occurs with much greater consequences than the early failures that were masked by the redundancy. This is especially a concern with autonomic systems, i.e., systems that manage themselves without intervention, even in the case of environmental changes.

Complex systems can result in emergent phenomena that could not be predicted by the characteristics of the components parts or subsystems. This is often true of systems whose subsystems have a degree of autonomy and their own objectives. Such systems are often referred to as "systems of systems" [Sage and Cuppan, 2001]. Complex systems can result in unintended consequences, in part but not only due to emergent phenomena. Thus, for example, the highway system developed during the Eisenhower administration, ostensibly for defense purposes, enabled urban sprawl, increased commuting miles, increased traffic congestion and, some would argue, a significant contribution to global warming. At the same time, the highway system had positive impacts on economic development and social mobility, for instance.

The discussion of modeling involved all engineering disciplines and several participants from medicine, be-

havioral science, and political science. It was often observed that we lack an ontology to discuss transdisciplinary modeling. It was suggested, several times, that a common taxonomy would be a good start in the direction of enabling transdisciplinary collaboration.

There was broad agreement, perhaps even consensus, that an important contributor to complexity is the multistakeholder, multiobjective nature of complex systems. There are large numbers of stakeholders with many interests and objectives. Mis- or nonaligned actors and incentives are common. The "span of control" of system designers and developers was mentioned.

There was also agreement that complex systems often involve many tradeoffs, most of which go beyond traditional disciplinary engineering. Hence, there is a need for involvement of many disciplines beyond engineering. This argues for the complex system initiative within NSF being Foundation wide and transdisciplinary.

Learning and adaptation are also important characteristics of complex systems. Selection processes result in evolution of systems whether they are human or technological. Consequently, the structure and dynamics of systems change in time. Homeostasis attempts to maintain the stability of the system at the same time that diversity and selection have the potential to improve the system.

These observations also included consideration of approaches to system flexibility and adaptation strategies. This contrasts with highly optimized systems that can be robust within the operating conditions for which they were optimized, but quite fragile outside these conditions. The tradeoff between optimization and agility came up repeatedly. In particular, a system designed to achieve the highest efficiency within given operating conditions may not be capable of agile adaptation to significantly changed operating conditions [Davis, Eisenhardt, and Bingham, 2007].

There was also discussion of the role of data, information and knowledge in complex systems. This included consideration of sensing, collection, and distribution of data and information, as well as their use in the control of complex systems. It was noted that sources of data, information, and knowledge can include both human and nonhuman resources. Those with backgrounds in control theory tended to discuss these issues using the classic concepts of observability and controllability.

Other issues underlying complexity included legacy systems, in terms of both addressing them and exploiting them as elements of complex systems. There was discussion of systems of systems and networks of systems, with emphasis on issues of coupling and integration. However, the phrase "systems of systems" did not have the currency it tends to have in DoD circles—see USC [2006]. There was mention of infrastructure as an enabler, thereby reducing complexity, at least for some classes of stakeholders. For example, information systems infrastructures can make information access and utilization seem much simpler.

Finally, there was a desire for the compilation of the practices associated with both successes and failures of complex systems. This included discussion of institutional strategies, especially those that cross the public and private sector components of many complex systems such as discussed in the Introduction.

4.2. Fundamental Research Topics

Table II shows how the three working groups aligned with the six categories of research topics identified. As indicated earlier, the empty (white) cells in this table do

Table II. Topics vs. Domains

	Infrastructure & Transportation	Healthcare Delivery	Bacteria Level Design
Premises	▓		▓
Design Objectives	▓		▓
Modeling	▓	▓	▓
Methods & Tools	▓	▓	▓
Decision Support	▓	▓	
Evaluation & Experimentation	▓	▓	▓

not reflect a lack of interest of some groups for several topics—the topics simply did not arise during their deliberations. On the other hand, decision support, for instance, was not salient in the discussions of bacteria level design, perhaps because decision-making was not seen as primarily occurring at that level.

There was considerable discussion of the premises upon which the research agenda should be built. Participants wanted to pursue rigorous research, which can mean different things to different disciplines. However, in general, people wanted to avoid ad hoc case studies and demonstrations. Rigorous theory building and evaluation should be the goal.

Another premise argued was the requirement for a transdisciplinary ontology and associated taxonomy. We need to move beyond disciplinary—and subdisciplinary—terminology and jargon. Otherwise, much research effort will have to be devoted to repeatedly finding common ground across the disciplines involved. It was suggested that ongoing efforts to develop modeling languages such as the Systems Modeling Language (SysML) and Object-Process Methodology (OPM) will provide the required support to bridge such disciplinary gaps.

Finally, a key premise was the availability of sustained funding for research in complex systems. The traditional NSF model of a modest portion of the faculty member's salary and one research assistantship for that faculty member's Ph.D. student is totally inadequate for the types of research discussed here. Indeed, the typical EFRI award (i.e., $2 million over 4 years) was viewed as marginal relative to the aspirations for this research area.

The first category of research topics centers on design objectives. This is often where the full context of the problem is captured—or, too often, assumed away. Research topics discussed include system agility vs. efficiency and evolution vs. stability. The concepts of evolvability and selection mechanisms were considered. Variation and apoptosis (i.e., programmed death) were discussed. These illustrate the many impacts of system biology on discussions as the workshop.

Other topics related to design objectives included modularity, robustness, and security. In general, many "ilities" were noted. The need for rigor was again discussed, especially in the context of the multiple perspectives with which a complex system can be viewed.

Modeling of complex systems received substantial attention, as the recommendations discussed in the next section illustrate. Models of multilevel, multiscale systems were deemed very important, including both spatial and temporal scales. The dynamic, networked nature of systems was emphasized.

Considerable interest was expressed in the pervasive uncertainties and risks associated with complex systems. This suggested important needs for research on decision-making, risk management, and decision support. Closely related are economic modeling as well as representation and assessment of the impact of information on system behaviors and performance.

The need for both qualitative and quantitative models was recognized, as well as representations drawn from multiple disciplines. Of particular interest was modeling the interactions of the private and public sector organizations associated with many complex systems. In general, the interest in modeling was broad and ubiquitous.

The central construct to emerge from these discussions of modeling was "architecture.[1]" This construct concerns the structure and relationships within a complex system, often expressed in terms of layers ranging from technical infrastructure to system operations. This construct is discussed in much more detail later in this paper.

Another category of research topics related to methods and tools. Topics suggested include design of networks and architectures. Methods and tools for multiscale sensing, pattern analysis, and failure mode analysis were advocated. Also of great interest were anticipatory methods whereby system characteristics could be projected, i.e., likely emergent behaviors and unintended consequences.

There was strong recognition of the need for research on decision support mechanisms. Of particular interest was decision support for multistakeholder, multiobjective decision making. Also suggested was research in collaborative decision making and visualization for distributed decision-making.

Considerable discussion surrounded the need for evaluation and experimentation with both models of complex systems and the real systems. Research topics proposed included experimental methods, test beds, measurement methods, case studies and benchmarking, and assessment of best practices

4.3. Summary of Results

The foregoing results can be summarized as follows. The complexity of a system (or model of a system) is related to:

- The *intentions* with which one addresses the system.

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[1]Definitions of the term "architecture are considered below in terms of constructs such as entities, relationships, behaviors, and performance associated with a complex system.

- The characteristics of the *representation* that appropriately accounts for the system's boundaries, architecture, interconnections, and information flows.
- The *multiple representations* of a system, all of which are simplifications; hence, complexity is inevitably underestimated.
- The *context*, *multiple stakeholders*, *and objectives* associated with the system's development, deployment, and operation.
- The *learning and adaptation* exhibited during the system's evolution.

This list received considerable discussion during the seven presentations following the workshop. Perhaps the most controversial conclusion was the notion that complexity relates to observers' intentions. Only a small percentage of participants disagreed in any strong sense with this conclusion. However, there were often comments about real vs. perceived complexity. This relates to the discussion of fundamental limits outlined later in this paper.

It was agreed that fundamental complex systems research should focus on:

- The full nature of design objectives for such systems (as known in time)
- Approaches to architecting and modeling systems relative to these objectives
- Methods and tools for model development and use
- Means for evaluation and experimentation with models and real systems
- Approaches, technologies and tools to enable decision support for those who invest in, develop, operate, and use complex systems.

This list resulted in much less discussion, in large part because the next section provided more avenues for participants' comments and suggestions. The above list did prompt questions regarding its relevance to biological systems. Perhaps surprisingly, participants from systems biology contributed to the formulation of this list and expressed comfort with it, perhaps because their interests were related to the design of biological systems.

5. RECOMMENDATIONS

The concluding plenary session of the workshop focused on summarizing areas of agreement. This resulted in three categories of agreements:

- Complexity-related phenomena of interest

- Important characteristics of complex systems
- Recommended research questions.

Each category had a small number of entries concerning which all participants agreed.

As noted earlier, subsequent to the workshop, these findings as well as the full content of this paper were presented at seven venues where roughly 200 members of the community interested in complex systems could comment on the findings and suggest elaborations. The comments and suggestions of these additional participants substantially enlarged and refined these areas of agreement. This section summarizes these elaborated findings.

5.1. Phenomena of Interest

It was broadly agreed that human and social behaviors in complex systems are of great interest and importance to understanding the nature of complexity. This includes phenomena such as human performance, mental models, and social networks. Indeed, many people argued that, were it not for human and social behaviors, systems would be much less complex. Complex physical systems are also of great interest, including biology, ecology, weather, and so on.

Also of interest are interdependencies across time and spatial scales and domains. The nature of rapid change and uncertainties were also judged to be important phenomena. This included change and uncertainties associated with the endogenous environment (e.g., technology), the exogenous environment (e.g., economy), and the unpredictable match of demands and system performance with system capacity. It was suggested that a significant mismatch can cause us to perceive a system to be complex, e.g., a mismatch of highway capacity and traffic volumes leading to congestion, although some participants argued that such mismatches affect performance but not complexity.

Another phenomenon of interest is the nature of the boundaries of systems. There was interest in the relationships of appropriate boundaries to authority to allocate resources, determine incentives, and control in general. If the boundaries are set too broadly, there is little of the system one can directly affect; if the boundaries are set too narrowly, important contextual elements are ignored. There was also interest in the difficulties posed by systems that are perceived to be boundaryless.

5.2. Important Characteristics

The characteristics of complex systems of most interest are emergent and adaptive behaviors and unintended consequences, as well as a range of "ilities," e.g., robustness, resilience, flexibility, agility, adaptability, and

evolvability. There are various tradeoffs implied, such as efficiency vs. agility, that need to be systematically explored.

There were also questions of the extent to which there are fundamental limits to understanding, representing, controlling, and otherwise engineering complex systems. Possible limits were characterized in terms of information access, knowledge of systems, well-posedness of models, design practices, nature of system "state," observability of states, controllability of states, and scalability of design solutions. Various analogs were suggested between classic limits such as Heisenberg's Principle and the study of complexity. This is a very rich topic with a robust literature that cannot be fully addressed in this paper.

5.3. Research Questions

The broad community that participated in the workshop as well as the subsequent presentations agreed to five overarching fundamental research questions.

- What *architectures* underlie the physical, behavioral, and social phenomena of interest? The goal here is scientific explanations of phenomena of interest in terms of conceptual frameworks, representations, structures, models, etc. A frequently mentioned example was the architecture of terrorism.

- How are *architectures* a means to achieve desired system characteristics? The goal here is engineering methodologies that enable consideration of issues such as modeling vs. sensing; harmonization of systems of systems; and the economics of complex systems. The architectures of sustainable systems were mentioned as an example.

- How can *architectures* enable resilient, adaptive, agile, and evolvable systems? The goal here is to understand what is fixed and what changes in terms of structures, relationships, controls, and incentives, as well as how to address the fundamental tradeoffs among efficiency, effectiveness, and agility. Information system architectures for supporting enterprises with fundamentally changing missions provide a good illustration of this need.

- How can and should one analytically and empirically evaluate and assess *architectures* prior to and subsequent to development and deployment relative to system goals and intended functions for stakeholders? The goal here is to understand and improve structure, relationships, controls, and incentives prior to and during deployment and system operation. An example is a transpor-

tation network where the nature of its use cannot be fully projected before it is deployed and users react to the new system.

- What is the nature of *fundamental limits* of information, knowledge, model formulation, observability, controllability, scalability, etc.? The goal here is to understand inherent limits to prediction, control, design, and operations so as to know where other mechanisms are needed to assure system performance, safety, and economy. A good illustration is a large-scale policy change related to energy, for example, where the strategies and responses of stakeholders cannot be accurately projected to the extent that the new policy has novel characteristics which these stakeholders have not previously encountered.

As noted earlier, some participants in the sessions following the initial workshop, as well as reviewers of the report on this overall initiative, wondered about the relevance of the above recommendations to systems biology. Certainly, the wording of these recommendations received considerable attention. This attention and associated discussions resulted in the system biologists being comfortable with, for example, the idea of the architectures of living systems.

These five recommendations beg a definition of the term "architecture." There are many available including IEEE Standard 1471, the Department of Defense's Architectural Framework, and IBM's Service-Oriented Architecture, to name just a few. The central constructs in all of these definitions are entities, relationships, behaviors, and performance. To this extent, the concept of architecture is simply an overarching term to capture many constructs that have long been available and employed.

It is useful to contrast architectures with the means used to create them (i.e., architectural frameworks) and the activity of creating them (i.e., architecting). From this perspective, an architecture is an instance of what is created by architecting using one of several possible architectural frameworks. The resulting architecture may represent a product (e.g., a vehicle), a process (e.g., the functioning of an information system), or perhaps an overall enterprise.

The notion of architecture provides a compelling overarching construct. This construct can be used to describe a complex system as well as the "layers" of the domain in which it operates. However, it should be kept in mind that constructs such as frameworks, representations, models, and so on have long been the stock and trade of systems thinkers and engineers. Nevertheless, the consensus of participants on the centrality of the construct of architecture is an important step in the

direction of a common foundation for understanding, designing, and operating complex systems.

6. RELATIONSHIP TO NSF

It was noted earlier that the effort reported here was initiated to formulate a possible research program within the Emerging Frontiers in Research and Innovation (EFRI) initiative. It is important to indicate the extent to which EFRI represents an important departure for NSF. In contrast to mission-oriented agencies, NSF has long been a paragon of disciplinarity, with its programs organized around disciplines and subdisciplines, each run by strong discipline-oriented program managers. EFRI has adopted a much broader approach and, as indicated by Richard Buckius in his introductory presentation at the workshop, this is an important element of the reorganization of the Directorate for Engineering. This section suggests how the research topics just discussed might fit within the EFRI framework.

6.1. EFRI Investment Criteria

As indicated in the earlier discussions, Richard Buckius presented the criteria for an EFRI solicitation:

- *Transformative:* Does the proposed topic represent an opportunity for a significant leap or paradigm shift in a research area, or have the potential to create a new research area?
- *National Need/Grand Challenge:* Is there potential for making significant progress on a current national need or grand challenge?
- *Beyond One Division:* Is the financial and research scope beyond the capabilities of one division?
- *Community Response:* Is the community able to organize and effectively respond (but not in very large numbers; i.e., is it an "emerging" area)?
- *Engineering Leadership:* Are partnerships proposed, and if so, does the NSF Engineering Directorate have a lead role?

6.2. Paradigm Changes

When these criteria were presented during the seven nationwide presentations of this material, many people asked what would qualify as a paradigm change. Several suggestions were provided:

- Classical Reductionism → Holism
- Classical Systems → Systems of Systems
- Classical Portfolio Theory → Options-Based Portfolios
- Classical Economics → Behavioral Economics
- Classical Biology → Systems Biology
- Classical Physics → Quantum Physics
- Classical Control Theory → Modern (State Space) Control.

The first two of these changes were, by far, mentioned most frequently. The third through fifth changes were also mentioned as central to understanding and designing complex systems. The sixth and seventh paradigm changes were mentioned as benchmarks.

6.3. Critical Programmatic Issues

There was great enthusiasm across the community for this research agenda. At the same time, there was concern about NSF's commitment to the resources needed for strong interdisciplinary research, as well as the resources needed for robust testbeds. There was also discussion of the need and potential for standard data sets to support research initiatives.

It was frequently suggested that additional research sponsors should be recruited to participate in this initiative. The idea was to create pooled research funds across agencies to enable critical mass, with NSF leading but with DoD, DoE, NASA, FAA, etc. also investing. This will enable, for instance, creation and maintenance of the aforementioned testbeds.

A strong overarching concern was the nature of peer review for likely proposals generated by a possible EFRI solicitation. Most people's experiences with NSF have involved very strong disciplinary and subdisciplinary critiques with emphasis on fitting into "business as usual" research agendas. The 250 people whose thoughts are reflected in this paper generally do not believe that such strong disciplinary orientations will serve well the research agenda presented here.

6.4. Notional Research Proposal

In light of the above EFRI criteria, participants discussed what a successful proposal might look like. These discussions led to a notional outline and themes for a proposal, listed below and shown in Table III.

- *Transformative:* Architectures that enable system learning and adaptation to multiple stakeholders and objectives, as well as contexts
- *National Need/Grand Challenge:* Domains of infrastructure, or healthcare, or the environment, or security, etc. -- these are, obviously, also global challenges.
- *Beyond One Division:* Projects with engineering, computing, and behavioral, social and life science researchers

Table III. Topics vs. Criteria

	Significant Leap or Paradigm Shift	National Need/Grand Challenge	Beyond One Division	Community Able to Respond	NSF Engineering Leadership
Architectures Underlying Phenomena	Architectures that enable system learning & adaptation to multiple stakeholders & objectives, as well as contexts	Infrastructure, Healthcare, Environment, Security, Etc.	Projects with engineering, computing, and behavioral, social & life science researchers	Research teams with unique & proven abilities to collaborate & succeed.	Emphasis on engineering design & evaluation of technology-based complex systems
Architectures As Means to Characteristics					
Architectures As Enabling Agility, Evolvability, Etc.					
Evaluation & Assessment of Architectures					
Fundamental Limits of Info., Knowledge, Etc.					

- *Community Response:* Research teams with unique and proven abilities to collaborate and succeed.
- *Engineering Leadership:* Emphasis on engineering design and evaluation of technology-based complex systems.

This notional proposal is intended as merely an illustration of the types of considerations that the EFRI program implies. This outline prompted considerable discussion among participants in the presentations of the workshop findings.

7. CONCLUSIONS

This paper has summarized the perceptions, interests, and recommendations of roughly 250 stakeholders in understanding and addressing complexity and complex systems. The initial 50 participants set the stage by formulating the workshop findings. The other 200 participants, across seven venues, challenged, debated, and elaborated these findings into a much richer set of recommendations to NSF. More recently, these findings have been presented at six additional venues involving several hundred new participants in the dialogue on complexity and complex systems.

Thus, the research discussed in this paper has a broad constituency that cuts across engineering, computing, management, physical sciences, life sciences, and behavioral and social sciences. This broad community is enthusiastic and committed to research that will help the nation address fundamental challenges associated with complex systems such as healthcare, infrastructure, environment, security, and competitiveness. This

community believes that the research agenda outlined in this paper provides a foundation and a vision for fundamental contributions to the nation's needs.

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