Engineering Complex Systems: *Implications for Research in Systems Engineering*

BETWEEN MY role as Chair of the School of Industrial and Systems Engineering (ISyE) at Georgia Tech and being co-editor of the *Handbook of Systems Engineering and Management* (New York:Wiley, 1999), I get many questions about systems engineering, namely, what this field includes and excludes.

A quick answer is, "take a look at the handbook." A bit more of an elaborate answer, especially if people are interested in what we are doing at Georgia Tech, can be cast in terms of the manufacturing, logistics, transportation, and health systems programs available at ISyE. This answer might also include mention of ISyE's cross-cutting areas of optimization, stochastics, statistics, economics, and human systems.

These types of answers often work, but occasionally people ask about the fundamental nature of "systems engineering," including why, or if, this construct does not cover everything and, hence, nothing. This is a great question and in this brief note, I attempt to provide an answer. I admit on the outset, however, that this note provides plenty of opportunities for disagreement, especially among advocates of one or more of the points of view elaborated.

To begin, it seems reasonable to assert that systems engineering involves the engineering of complex systems. This emphasizes engineering as a verb, i.e., something one does. Engineering as a verb implies the creation of entities that are more than just sums of parts. Creation in this manner requires analysis and synthesis of complex systems.

- By system, I mean a group or combination of interrelated, interdependent, or interacting elements that form a collective entity. Elements may include physical, behavioral, or symbolic entities. Elements may interact physically, mathematically, and/or by exchange of information. Systems tend to have purposes, although in some cases the observer ascribes such purposes.
- By complex systems, I mean systems whose perceived complicated behaviors can be attributed to one or more of the following characteristics: large numbers of elements, large numbers of relationships among elements, nonlinear and discontinuous relationships, and uncertain characteristics of elements and relationships. I include the idea of perceived complexity because apparent complexity can decrease with learning.

Based on my perusal of a wide range of literature, as well as many discussions with colleagues at Georgia Tech and elsewhere—see acknowledgment—it is clear that there are several views on what "analysis and synthesis of complex systems" actually implies. In particular, there are multiple perspectives on the source of the "complexity" of the systems we are seeking to engineer.

I hasten to note that a primary differentiator among these views concerns systems science vs. systems engineering. Within systems science, there are both formal system views and natural system views. Formal system scientists focus on worlds that humans create while natural system scientists pursue worlds that nature creates. Of course, there is often the strong desire to perceive formal worlds as close analogs of natural worlds. Systems engineers adopt both formal and natural views depending on the circumstances.

SYSTEMS OF HIERARCHICAL MAPPINGS

Many people view systems engineering in terms of the processes for designing, developing, deploying, and sustaining complex systems, notably, defense and public systems, but also airplanes, manufacturing facilities process plants, etc. This view tends to be driven by hierarchical decomposition of a very complicated design task into component tasks, as well as management of the execution of these tasks and integration of task outcomes.

The emphasis is on defining a large number of reasonably straightforward tasks whose outcomes flow together to create a successful complex system, with appropriate resolution of multi-attribute tradeoffs across multiple stakeholders. Performance of these more straightforward tasks may draw upon expertise from various engineering disciplines, computer science, economics, and so on. The key, however, is that complexity is managed by dividing and conquering.

Note that the complexity here is typically due to large numbers of interacting elements. The elements are usually well defined, in fact, designed. Relationships among elements are often "linear" in the sense that overall system behavior is a reasonably straightforward composite of the behavior of its many elements.

SYSTEMS OF UNCERTAIN STATE EQUATIONS

Another view of systems engineering focuses on the "state" of the system of interest. The mechanisms whereby the state of the system evolves are of central interest as they affect system response and stability. The nature of appropriate feedback mechanisms for controlling system state is a central design issue. Observability and controllability are key constructs. Optimization of control is an overriding goal. However, inabilities to fully specify state-transition mechanisms and a wealth of other uncertainties limit this pursuit to formulation of constrained optimality.

The emphasis in this view is on formal depiction and manipulation of mechanisms underlying complex behaviors. This more formalistic approach seldom "scales up" to the types

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of problems addressed by the hierarchical mapping view of systems engineering. However, fundamental knowledge gained from formal approaches may provide insights into successful approaches in more complicated domains.

Complexity in this view is often due to a large numbers of state variables and significant levels of uncertainty, including uncertain state-transition mechanisms. Pursuit of optimal control solutions can both be mathematically and computationally complicated. Such pursuits are often made possible by assumptions of linearity.

SYSTEMS OF DISCONTINUOUS NONLINEAR MECHANISMS

Yet another view focuses on apparently simple underlying phenomena that yield complex behaviors for systems with very few elements, perhaps even just one element with particular interaction terms. The nonlinear and/or discontinuous nature of the elements of interest lead to behaviors labeled as catastrophes, chaos, and so on. The key point here is that systems appearing simple can produce very complex behaviors. The resulting hypothesis is that many apparently complex phenomena can be attributed to surprisingly simple mechanisms.

The nonlinear mechanisms view portrays complexity as a departure from our expectations of continuous, linear phenomena. There need not be large numbers of interacting elements. This perspective argues for understanding complexity by exploring underlying mechanisms. Identification of such mechanisms may lead to design solutions, for example, by adapting natural mechanisms to human-made systems.

It is quite imaginable, perhaps typical, that nonlinear mechanisms underlie the state-transition mechanisms central to the earlier state equations view. Formal systems approaches can flounder when addressing fairly small numbers of interacting nonlinear mechanisms. Complexity in such situations escalates much more quickly with nonlinear than linear elements.

SYSTEMS OF AUTONOMOUS AGENTS

A fourth view is concerned with understanding the emergent properties of complexity. Rather than focusing on decomposition, this view emphasizes composition of large numbers of simple behaviors into overall system behaviors that exhibit hallmark characteristics of complex systems. The simple behaviors are created by autonomous "agents" acting independently in pursuit of their individual goals. These goals need not differ across agents. Further, agents may communicate about goals, resources, actions, etc. Reactions of agents to each other's behaviors result in emergent phenomena that could not have been predicted by dissecting mechanisms within individual agents.

Insights gained from studies of such phenomena include understanding the nature of incentives, motivations, and prohibitions that will influence individual agents to contribute to creating desirable collective behaviors. In this view, understanding and managing complexity is more an experimental than axiomatic undertaking. This approach presents difficulties in that many things can be demonstrated but few can be proven.

Complexity in this view is in part due to a large number of elements, although were all the elements simply linear, noninteracting agents, the state equation's view might be successfully employed. However, typical agents are not linear, they interact with each other, and they learn from their own and others' behaviors, which may modify their intentions over time. Thus, formal approaches are seldom tractable.

TABLE I
CONTRASTING VIEWS OF COMPLEX SYSTEMS

No.	View	Approach	Focus
1	Hierarchical Mappings	Design decomposition	Engineering solutions
2	State Equations	Axiomatic derivation	Control performance
3	Nonlinear Mechanisms	Behavior demonstration	Basis of complexity
4	Autonomous agents	Empirical assessment	Emergent behaviors

CONTRASTING VIEWS

Table I contrasts the four views just outlined. Clearly, the approaches and foci of these four views are quite different. This contrast might merely be interesting were it not for the fact that, in some cases, all four views are addressing related phenomena, e.g., effects of turbulent flow on aerodynamic behavior and vehicle performance in high-density traffic.

In this example, view no. 1 might be employed for designing the vehicle, no. 2 to explore the vehicle dynamics, no. 3 to model the turbulence, and no. 4 to understand traffic effects. Of course, the choice of approach would depend on the problem at hand, e.g., poor vehicle handling qualities vs. traffic congestion problems.

Nevertheless, in this simple example we see complexity at multiple, related levels. The literature within each discipline where these views are pursued tends to argue for the essence of complexity operating at their level. However, from a broader, cross-disciplinary perspective, none of these arguments are tenable.

SPANNING THE VIEWS

If we think in terms of multi-view representations of systems, there are several issues that span the four views just elaborated and contrasted. One of these issues concerns the nature and flow of information. Uncertainties associated with this information are also of interest.

The hierarchical mappings view addresses this issue explicitly, both in terms of the information flows within the system and information flows about the system, i.e., for design, development, maintenance, etc. The state equations view addresses state information—including uncertainty associated with this information—quite rigorously, but does not capture information about the system, for instance, for maintenance. The nonlinear mechanisms view is also purely focused on phenomena related to state transitions.

The autonomous agents view addresses information flow bottom up from information access and exchange among individual agents, including access and posting of information from and to formal sources. While individual agents may act probabilistically, a larger source of uncertainty is often unpredictable emergent behaviors. This is not just an issue, for example, of observation variability in terms of variances around known means, but instead relates to the possibility of whole courses of collective action being rather different than expected.

Another spanning issue concerns decision making and control. This concerns representation of the framing and making of decisions to pursue courses of action, as well as the control associated with executing these courses of action. The hierarchical mappings view addresses decision making, decision support, and execution quite explicitly. However, approaches to decision making and control are usually far less formalized than with the state equations and nonlinear mechanisms views. While the former view focuses on supporting decision makers' needs and preferences, the latter two views place much more of an emphasis on prescriptions for how decision making and control should be addressed, e.g., in terms of optimal decision and control strategies.

The autonomous agents view addresses this issue much more simply. Agents' decision making and control strategies are usually quite elementary. The complexity arises from large numbers of agents employing these strategies. The resulting interactions, including effects of incentives, regulations, etc., often serve to demonstrate how seemingly rational "rules of the game" can yield clearly undesirable overall system behaviors. Decision making and control with this view is much more distributed than with the other views.

A third spanning issue concerns representation of human behaviors, both individually, and organizationally. The hierarchical mappings view often represents such behaviors explicitly, at least in terms of information and control requirements for supporting these behaviors. This view also tends to place great emphasis on human involvement in the process of engineering systems. Thus, humans in this view both decide and control, as well as design and develop.

The state equation's view includes such representations to the extent that humans can be depicted "in the loop" of state transitions and control. The nonlinear mechanism's view may depict human-related phenomena, but human information processing characteristics are rarely explicit. For both of these views, strong assumptions are often made regarding a person's ability to decide and control optimally, perhaps within mathematically tractable constraints.

The autonomous agents view is often primarily focused on human behaviors, particularly large collections of humans. Individual behaviors are represented in terms of decision and control rules, perhaps including possibilities for learning. Organizational behaviors are represented in terms of rules for information flows, decision processes, and performance incentives. Some uses of this view represent organizations as agents operating, for example, within marketplaces.

Clearly, the ways in which one chooses to address the spanning issues just outlined affect the attractiveness of the alternative views of systems and complexity. Both the problems at hand and the tools available also strongly affect such choices. To the extent that information flow and portrayal for support of human decision making and control are central systems issues, the choice among alternative views is fundamental.

RESEARCH IN SYSTEMS ENGINEERING

Systems operate at a multiple of levels and exhibit apparently complex behaviors at all these levels. The problem at hand very much affects the best level at which to address the problem. For instance, managing the complexity of aircraft development is very different from understanding the complexity of bees' foraging behaviors.

This suggests that the nature of systems engineering is determined by the range of problems addressed. From this perspective, my "easy" answers to the questions people have, mentioned earlier, are pretty good. Yet, not satisfying, at least not to me.

My sense is that systems engineering at its richest is able to cross levels of description and integrate the above views to engineer complex systems in a more integrated and effective manner. Good systems engineering is able to uncover which views are critical to effectiveness and employ the appropriate concepts, principles, methods, and tools for assuring effectiveness.

This suggests that investments in systems engineering research should focus on elaboration of the multiple views and creation of means for translating among these views. To a great extent, we have many pieces of the puzzle within the various disciplines of engineering and science. What we do not have is a true sense of the whole puzzle in terms of both how and why the pieces fit together.

Systems engineering is not another discipline like industrial, electrical, mechanical, and chemical engineering. It should be an integrative discipline that crosses the boundaries of these disciplines and, of course, others. Thus, systems engineering is "everything," in the sense of the exploration, understanding, and design of how everything fits together. From this perspective, systems engineers provide a brokerage and communication function that enables them to see the system from the perspective of all stakeholders, ranging from the different engineering disciplines involved to users, customers, and the public.

Systems engineering research should focus on how to do this and how to do it well. This suggests the idea of an "architecture" of knowledge across engineering and science that enables for quickly linking puzzles and puzzle pieces. Such an architecture could also be invaluable for identifying high-leverage pieces that provide the essence of the picture as well as missing pieces.

A tremendous amount of productive research is performed within the many disciplines of engineering and science. The outcomes of this research can only be fully leveraged by understanding and creating mechanisms for integrating knowledge and technologies to create efficient and effective complex systems. This should be—and is—the charter of systems engineering.

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