ENGINEERING SYSTEMS MONOGRAPH

THE FUTURE OF ENGINEERING SYSTEMS: DEVELOPMENT OF ENGINEERING LEADERS

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INTRODUCTION

From birth through death, inhabitants of developed societies live supported in a complex, interconnected set of overlapping systems. These systems span the range from health care systems to financial systems to transportation systems to information systems. The US Government has identified several of them, including infrastructures for communication, water, energy, and finance, as critical for an advanced society.

Many such systems, while important to our effective function, are not fundamentally the province of engineers. For example, from a young age we interact with one or more education systems, and we often end up interacting with some version of a health care system. These systems are primarily social systems in that they involve how societies choose to treat their citizens. They have been analyzed through the lens of policy and economics, combined in both cases with a developing scientific understanding of how our bodies function and our minds learn.

Increasingly, we also interact with a class of systems that depend for their existence on technology or technological artifacts. These are the province of **Engineering Systems**. These systems provide much of the function of modern society. Examples include the global air traffic control system, the worldwide Internet, the worldwide communications grid, and the national mobility system composed of automobiles, trains, planes, highways, train stations, and airports. These systems have critical technological pieces, but also have significant enterprise level interactions and socio-technical interfaces that determine the design or operation of the system. Of course, many of these systems are connected to each other, and together make up systems of systems. For example, the air traffic control system, the communications system and the mobility system all have inter-connections with each other. The terrible terrorist attacks of 9/11 showed clearly how some of the critical infrastructures in the US are connected to each other, and how failures in one can have long term effects on another.

These systems have been analyzed partly through the tools of operations research, systems analysis and economics, and designed using the processes of systems engineering. The engineering management techniques for the creation of these systems have often been ad-hoc, while the policies that govern the use of these systems have often emerged after the fact. The budgeting for these systems is largely an art, and thus many of these large complex systems go over budget and schedule. In addition, some of them have had initially surprising societal consequences. Witness the use of the Internet for spam and the interaction between this emergent use and the technical design of the Internet.

What is needed is the development of a holistic view of these systems that takes into account all the issues associated with them. This integrative, holistic view of technologically enabled systems is what the field of Engineering Systems concerns itself with. In modern academic engineering, with its large and valuable emphasis on the applied science behind engineering, this integrative view has often been neglected, since it cuts across many disciplines. Of course, this is because much of the power behind the engineering science approach lies in a reductionist mindset, combined with the sharp manipulative power of mathematics. To fully appreciate these complex, interconnected systems requires a view that bridges traditional engineering approaches with insights from management and social science. As with all modeling, the ultimate goal of this combination of disciplines should be to model and predict the behavior of these complex systems in their full contexts.

In this paper, we shall explore a projected future intellectual development of what we are calling Engineering Systems in the context of the qualities we would like to see in the leaders that develop in this area.

DEFINITION AND CURRENT STATE OF ENGINEERING SYSTEMS

The word “systems” has a very broad usage. The definition of a system is a collection of pieces whose collective function is greater than the function of the individual pieces. Within the mathematically based, rigorous engineering and scientific world, this vagueness has led to some criticism since it is so broad. If “systems” applies to everything then it also applies to nothing. In order to be specific, we shall focus on Engineering Systems. Our definition of Engineering Systems is quite specific and leads to the kind of people who need to be developed in order to address these systems.

We are interested in systems with the following characteristics:

- Technologically Enabled
- Large Scale (large number of interconnections and components)
- Complex
- Dynamic, involving multiple time scales and uncertainty
- Social and natural interactions with technology
- May have Emergent Properties

The phrase “technologically enabled” applies to systems with one or more artifacts of technology at their core. That is, the systems would not exist apart from the technological artifact(s). A good example is the air traffic control system, which has at its core, airplanes, radars and airports. The systems we are interested in understanding are also large in the sense of having a large number of interconnections. This may map to large physical scale (it clearly does for an air traffic control system), but it does not necessarily have to do so (for example, one cannot impute any physical scale to the Internet, but it has a large number of interconnections). The description of engineering systems as complex is meant to imply that they have nonlinear properties in that the outputs of the system are not simply related to the inputs. In part, this nonlinear behavior flows from multiple timescales underlying the system, coupled with the overwhelming presence of uncertainty. In part, it also flows from the fact that the systems we are interested in have significant pieces and decisions determined by their interaction with the social or natural world. Finally, we observe that these systems often have emergent properties usually in how society uses or responds to these systems. For example, the current use of the Internet for spam was not at all predicted or understood when the underlying technical architecture of the Internet (which makes it easy) was laid down. Another example is the development of hub and spoke air transportation systems, and the growth of airport malls to serve people who have time to kill waiting for connecting flights.

We argue that understanding Engineering Systems requires the following:

- An Interdisciplinary Perspective—technology, management science and social science
- The incorporation of system properties, such as sustainability, safety and flexibility in the design process. (These are lifecycle properties rather than first use properties.)

- An Enterprise Perspective
- The incorporation of different stakeholder perspectives

A second set of properties, often called the “ilities,” emphasize the fact that there are important intellectual considerations associated with long-term use of engineering systems. These may be quite different from the first use for which the systems were designed. These other properties may come to dominate the use of the systems.

One of the best ways to understand Engineering Systems is through examples, of which some important ones are:

- Military Aircraft Production & Maintenance Systems
- Commercial & Military Satellite Constellations
- Megacity Surface Transportation Systems
- The Worldwide Air Transportation & Air Traffic Control System
- The World Wide Web & the Underlying Internet
- Automobile Production & Recycling Systems
- Consumer Supply Logistics Networks
- Electricity Generation & Transmission Systems

These systems are all manifestly technologically enabled, have significant socio-technical interactions, and have substantial complexity. It is also the case that to varying degrees an understanding of them requires an understanding of the enterprises that constructed them, or within which they operate. The accompanying paper by Moses[1] on some of the foundational issues with Engineering Systems also outlines other types of engineering systems.

Given that we have defined Engineering Systems, we turn to explore the current state of our understanding of these systems on the way to defining the attributes of the people who will design and operate these systems. The well-known hierarchy of knowledge by which we can explore our understanding is:

1. Observation
2. Classification
3. Abstraction
4. Quantification and Measurement
5. Symbolic Representation
6. Symbolic Manipulation
7. Prediction

Many engineering fields have started out at level 1 and moved to level 7. A good example is the discipline we now call thermodynamics. This started with observations of steam engines that were made to work by a trial and error process. As time progressed, various laws were discovered. Eventually, the laws of classical thermodynamics were induced, which allowed engineers to move to level 7 for thermodynamic engines. It was realized that the three laws of

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[1] Joel Moses, “Foundational Issues in Engineering Systems: A Framing Paper,” (paper presented at the MIT Engineering Systems Symposium, March 29-31, at MIT, Cambridge, Mass.).

thermodynamics undergirded all the previous observation and allowed new types of machines to be constructed. This is also true of the field of aerodynamics. At one time, people relied only on the observations of how birds flew to develop an understanding of aerodynamics. Once the conservation laws were understood and applied to compressible gases, the modern understanding of aerodynamics was born. Of course, aerodynamics is now at the level of prediction as manifested by the ease with which aircraft can be designed that fly well. Now the issues with modern commercial aircraft are generally not aerodynamics, but issues of manufacturing and lifecycle cost efficiency.

The current state of Engineering Systems as defined above is somewhere between levels 2 and 4. Some of the systems have been abstracted, measured and quantified. As with the development of any engineering field, the goal is to move up the hierarchy of knowledge to the point where the behavior of these complex systems can be predicted. Then it will be the case that when society builds complex engineering systems, it will do so with a good understanding of the likely benefits, costs and consequences of constructing the systems. This will allow these systems to be built on budget, on schedule and with the desired performance by individuals with a holistic perspective.

In the next section, we shall explore the underlying disciplinary bases on which engineers will move up the hierarchy of knowledge to ultimately produce these engineering leaders.

THE INTELLECTUAL UNDERPINNINGS OF ENGINEERING SYSTEMS

The development of any multidisciplinary field requires progress in the underlying disciplines. For example, the development of progress in fusion energy engineering has required progress in plasma physics. Note, however, that while understanding plasma physics is essential to engineering a fusion reactor, it is not sufficient, since it does not include the totality of the issues required to make a real reactor work. This requires the union of plasma physics with nuclear engineering with material engineering with risk analysis to approach the design and operation of a real reactor. In a similar manner, we will argue that there are a number of underlying disciplines for understanding the design and operation of real Engineering Systems. It is engineers educated at the union of these disciplines who will make progress. We will argue that the four underlying disciplines for Engineering Systems are system architecture/systems engineering and product development, operations research and systems analysis, engineering management, and technology and policy. The union of these four disciplines around the system applications will lead to greater understanding of Engineering Systems.

One way to consider the intersection of these disciplines around a complex engineering system is to consider a specific example like the National Missile Defense (NMD) system. This is manifestly an engineering system in that it is technologically enabled, complex, large scale, dynamic and has interesting interactions with foreign policy. The NMD system first needs to be architected (taking into account both legacy systems as well as emerging technologies and techniques for detection) and then to have detailed systems engineering done for it. It will be analyzed with the techniques of operations research (including game theory) and systems analysis. It will be built by large organizations whose organizational dynamics will play a role in the architecture, choice of partners and the order in which pieces are designed and constructed. Finally, the design choices have interesting and significant (foreign) policy implications that will affect the initial set of architectural choices. Thus issues of technology and policy are critical to the design and operation of this system,

In the next four subsections we explore what needs to be done in each area to advance Engineering Systems.

SYSTEM ARCHITECTURE AND PRODUCT DEVELOPMENT

Systems Engineering and product development describe the set of ordered processes whereby a design can be taken from the statement of requirements to a specific manifestation in a design. System architecture describes the larger process whereby concepts are developed that map desired functions into possible forms. These forms may then undergo the process of systems engineering. While the development of “tree structured” and “layered” systems engineering has undergone considerable development, the same is not true of system architecture. This is still largely an art whereby architects try and come up with concepts to satisfy expressed needs. Much of the intellectual development that is needed here will come from the quantification and manipulation of system architectures. Whitney et al. discuss this in the companion paper[2].

OPERATIONS RESEARCH AND SYSTEMS ANALYSIS

Operations Research has highly developed the theory of optimization for different types of cost functions. In a similar vein, various systems analysis techniques have been developed to analyze the behavior of systems once they can be reduced to quantifiable networks. Both of these areas need development to address the issues of engineering systems. Operations Research needs to develop an understanding of the nature of optimization when lifecycle issues are important as well as when issues of flexibility need to be quantified. In this, there is significant development that can be undertaken using the techniques of financial engineering, particularly real options, as a way to value flexibility. De Neufville et al. analyze this in the companion paper.[3]

Systems analysis has developed the macroscopic technique of system dynamics[4]. This is a very powerful way to model many kinds of engineering systems. While it produces many insights, it often comes down to understanding what the coefficients are that relate the stocks and the flows. A newer analysis methodology that offers great hope is agent based modeling, whereby systems are modeled at a much more elemental level, and a complex set of interactions is built from a simple set of rules. The development of analysis techniques for Engineering Systems will need the integration of these modeling techniques to form an operational palette for the engineering systems analyst.

ENGINEERING MANAGEMENT

All real engineering systems are built within enterprises and operated within society. The interaction between the designing enterprise and the engineering system is deep. While organizational theorists have well developed theories of how organizations function and make decisions, this understanding needs to be integrated into the design phase in a quantifiable way. Then it will be the case that a priori the effect of the enterprise organization on the engineering system will be predicted rather than being a surprise.

TECHNOLOGY AND POLICY

Significant socio-technical interactions are a property of the large-scale systems of interest in the study of Engineering Systems. Too often, these interactions have been observed after the systems were designed and considerable resources have been spent. Thoughtful analysis of these interactions has also been the realm of political scientists or sociologists. As Engineering Systems develops, these interactions will be modeled in a way that is quantifiable, and can be

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[2] Daniel Whitney et al., “The Influence of Architecture in Engineering Systems,” (paper presented at the MIT Engineering Systems Symposium, March 29-31, at MIT, Cambridge, Mass.).

[3] Richard de Nuefville et al., “Uncertainty Management for Engineering Systems Planning and Design,” (paper presented at the MIT Engineering Systems Symposium, March 29-31, at MIT, Cambridge, Mass.).

[4] John D. Sterman, *Business Dynamics: Systems Thinking and Modeling for a Complex World* (Boston: McGraw-Hill/Irwin, 2000)

included in the systems analysis of these complex systems. Several models of this type can be found in the companion paper by Cutcher-Gershenfeld et al[5].

THE FUTURE OF ENGINEERING SYSTEMS

In order for engineering systems to move to level 7 in the hierarchy of knowledge, the intersection of the underlying four disciplines will have to be reduced to mathematics, or at least computer simulation, applicable to many different types of engineering system. This will be greatly aided by two things: 1) the discovery of a small number of generalizable, quantifiable principles that go beyond the level of heuristics; and 2) the development of a small number of methods that can be applied to many types of engineering systems. The principles will be akin to the conservation laws in fluid mechanics, while the methods will be quantified in computer simulations to model complex systems.

Once these principles and methods are understood, engineering systems will be architected and designed taking into account future, partially unknown requirements and uses. Long term uses incorporated through the “ilities” will be designed into the systems in predictive ways. Thus systems will be designed that can be shown to have embedded properties such as safety and security. Systems will be designed with issues of sustainability and flexibility embedded in the original formulation of the system, and it will be possible to predict quantitatively the extent to which these properties are present.

The full realization of all of these desirable properties of large scale, complex systems will come about from bringing together economics, game theory, complexity theory, graph theory, real options theory, along with systems architecture and multidisciplinary optimization. These must be combined with powerful computer simulations in order to model and predict these systems.

A deep question is whether the inclusion of the human dimension of engineering systems can ever be fully included in the quantitative prediction of engineering systems. Certainly traditional decision analysis and game theory allows many aspects of human choice to be included, but these methods have well known limitations. System Dynamics allows the feedback loops in many systems to be seen clearly, while in principle, agent based models allow for large scale simulations from an elemental level. Whether or not these methods will ever get to include all the interesting intersections of human activities and technical systems is open to question.

When Engineering Systems has been fully developed as a field, we predict two major consequences. In engineering schools across the world, undergraduates will be educated in the fundamental engineering sciences as they are now, but they will also be given an appreciation of the Engineering Systems context in which some of them will be doing their engineering. At the graduate level, there will be well-developed masters and doctoral degrees in the various aspects of Engineering Systems. The development of the field of engineering systems will be used to predict the development of new types of engineering systems. For example, as the previously discussed National Missile Defense system evolves over time, the techniques of engineering systems will be brought to bear to predict how it should be designed and how it should behave.

A NEW KIND OF ENGINEERING PROFESSIONAL: ENGINEERING SYSTEMS LEADERS

As this broader understanding of Engineering Systems is developed, a new kind of engineer will emerge: the Engineering Systems professional[6]. These integrative leaders will consider

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[5] Joel Cutcher-Gershenfeld et al., “Sustainability as an Organizing Design Principle for Large-Scale Engineering Systems,” (paper presented at the MIT Engineering Systems Symposium, March 29-31, at MIT, Cambridge, Mass.).

technological components as part of larger engineering systems and will utilize different approaches than those based on the traditional engineering science paradigm. Engineering systems professionals will consider the context in which the system operates as a design *variable* rather than a constraint. Thus, they are concerned with the design of the organization that has to manufacture the system or product; the regulations and public policies governing its use and disposition; the marketing; and the relationship with suppliers, distributors and other participants in the value chain. From this perspective, the design process includes the physical attributes that are the domain of traditional engineering; the process attributes that are the domain of both engineers and managers; and the context attributes that traditionally have been the domain of managers, governments, and social scientists.

These leaders are necessary in society and in the academy to develop an interdisciplinary approach to engineering systems problems that considers the context in which the systems are initiated, designed, manufactured, constructed, implemented, and maintained. That context is undergoing significant change as a result of globalization, the information revolution (particularly the Internet), and emerging social concerns (particularly sustainability). This perspective is reflected by President Charles Vest's comments in the MIT President's Report[7]: "Humankind's advances will depend increasingly on new integrative approaches to complex systems, problems, and structures. Design synthesis and synergy across traditional disciplinary boundaries will be essential elements of both education and research."

These engineering systems professionals will be critical in the future development of the academy. In the academy, these engineering systems professionals should be about 20% of the engineering faculty of leading engineering schools. They will help to give engineering students the holistic perspective necessary to be productive engineers and leaders in modern society. These engineering students, once they become engineers, will not take a back seat to people trained as lawyers, for example, but will help to lead society in a manner that is technically competent as well as socially aware. This new kind of engineering systems professor will undertake rigorous integrative work and continue to push the traditional engineering science oriented departments to think more broadly about the nature of large scale engineering in this century.

This engineering systems faculty and the students it produces will help the academy address the issues framed by Donald Kennedy in his insightful book *Academic Duty*[8]. In the final chapter, he asks, "Can the universities really make a difference with respect to the Big Problems facing us?" His list of challenges ranges from arms proliferation and disarmament to ethical issues in genetic testing and counseling to utilization incentives in health-care systems. These problems are intellectually exciting and analytically demanding. However, they do not come in disciplinary packages. Those who wish to work on them face suspicion in the academy, which Kennedy asserts stems partly from the traditional academic disdain for "applied" work and partly from common perceptions of multidisciplinary scholarship as "watered down" or "soft." However, these real and complex problems of large scale require the attention of thoughtful intellectuals. Kennedy asks whether the academy can overcome the resistance of departmental structures to "re-engineer" itself in the face of these challenges. We argue that part of the answer to this question lies in educating leaders who can operate at the interface of technology and society, with an integrated vision of engineering systems and with the ability to predict their behavior. These professionals in the academy will help us to overcome the world of "two cultures" that Snow[9] made famous in the last century. And the academy is exactly the kind of place where these leaders can thrive and where their students can be educated. But it will not be business as usual. An academy divided along narrow disciplinary lines with a disdain for multidisciplinary

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[6] G. Wayne Clough et al., "The Engineer of 2020: Visions of Engineering in the New Century," (Washington, D.C., National Academies Press, 2004)

[7] Charles M. Vest, "MIT Presidents report for AY 99/00," June 2000

[8] Donald Kennedy, *Academic Duty* (Cambridge, Mass., Harvard University Press, 1997)

[9] C. P. Snow, *The Two Cultures* (Cambridge: Cambridge University Press, 1993)

work will not do this. The academy needs to change the way that it thinks about means and ends and the very purpose of innovation itself. There is a need to forecast the implications of new and emerging engineering systems, and then to take steps meet the challenges and opportunities they are likely to pose. The academy needs to strategically position itself if it is to produce the kind of leaders who can help society deal with these challenges. We argue that one of the best places for these leaders to emerge is from a broadened perspective on engineering arising from progress in Engineering Systems, for a multidisciplinary perspective will be key for future leaders in emerging systems, as well as for the many other important issues that bridge the culture gap that we have already described.

In closing, we argue that the big issues in society, the cultural divide that is created and perpetuated by our educational system focused into the two poles of science and the arts, and the accelerating pace of technological change in society demand a change in the academy. They also demand a new kind of engineering leader flowing from this expanded vision for engineering. Thus, in the words of our one of our colleagues,[10] the academy must produce engineering leaders who are: 1. Skilled intellectually at dealing with the many crucial technological dimensions of our society, 2. Have the practical results orientation that is characteristic of engineering professionals, 3. Have the courage based on early experience to take on the most difficult systems problems, and 4. Have the leadership skills to bring others forward as they themselves move along. By doing so, they will help ameliorate the societal response to the technologically driven changes that keep driving and transforming society. Apart from this transformation in the academy, the status quo will prevail and we will not move forward to prediction and improvement of Engineering Systems for the betterment of society. The development of educated Engineering Systems professionals is one of the ways that engineering will respond to the needs of society and provide leaders for the future.

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[10] Larry Linden, e-mail, 2000.