

# The Development of Leaders who are Engineers

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## Introduction

In this modern world, we live supported in a complex interconnected set of overlapping systems. From birth through death, inhabitants of developed societies interact with one system or another. These systems span the range from health care systems to financial systems to transportation systems to information systems. The US Government has identified several critical infrastructures that underlie an advanced society. These include a communications infrastructure, a water infrastructure, an energy infrastructure and financial services.

Increasingly we also interact with a class of systems that depend for their existence on a technology or technological artifacts. These are the province of **engineering systems**.

These systems provide much of the functioning 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 are have critical technological pieces but also have significant enterprise level interactions and socio-technical interfaces which determine the design or operation of the system, 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 the 9/11 showed clearly how some of the critical infrastructures in the US are connected to each other and failures in one can have long term effects on another.

To quote our distinguished Dean, Thomas L. Magnanti

*“Today, many large-scale, extraordinarily complicated systems call out for a systems-driven engineering approach. Just consider a few of these critical systems challenges:*

- redesigning transportation systems such as airline, rail, and urban highway systems that have increasingly reached their capacity and created enormous delays;*
- using information technologies to create products that are more timely, less expensive and increasingly responsive to consumer needs;*
- reconciling the inevitable growth in world-wide energy demand with potential environmental costs;*
- creating product development systems that address the full spectrum of conceiving, designing, and developing a new product; and*
- developing manufacturing systems that are more attuned to the human impacts they generate, from wage attenuation and job losses to dislocations linked to globalization.*

*We believe that the converging forces of increased system complexity and the social impact of technology -- combined with a need for increased leadership by engineers -- create opportunities for new directions in engineering education and practice. The most successful engineers must possess superb professional skills as engineers, including a*

*keen understanding of social, regulatory, environmental, cultural, and other forces. In short . . . we need Engineering Systems”*

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. In order to fully appreciate these complex interconnected systems requires an integrative holistic view that bridges traditional engineering approaches with insights from management and social science. The rigorous development of this view will enable the development of leaders who are engineers. In this talk, 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 functioning is greater than the functioning of the individual pieces. 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

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

The 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.

## The intellectual underpinnings of Engineering Systems

The development of any field requires progress in the underlying disciplines. For example, the development of progress in fusion energy engineering has required progress

in the underlying discipline of 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 intersection of these disciplines who will make progress. We will argue that the four underlying disciplines for engineering systems are system architecture/system engineering and product development, operations research and systems analysis, engineering management and technology and policy. The intersection of these four disciplines around the system applications will lead to greater understanding of engineering systems. The development of engineers schooled in these areas will allow these people to be holistic and to lead.

## The future of Engineering Systems

In order for engineering systems to move to the level of prediction 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. These are the discovery of a small number of generalizable, quantifiable principles that go beyond the level of heuristics and 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 these 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 choices 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 agency and technical systems is open to question.

# 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 and is emerging. These will be engineering systems professionals. Engineering Systems professionals will be the new kind of integrative leaders that engineering needs to produce<sup>1</sup>. These integrative leaders will thus be professionals who consider the technological components as part of a larger engineering system and 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 the interdisciplinary approach to engineering systems problems described above 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 (the Internet in particular), and emerging social concerns (sustainability in particular). This perspective is reflected by President Charles Vest's

comments in the MIT President's Report<sup>2</sup>, "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 who will be leaders in modern society. These engineering students once they become engineers will not take a back seat to people trained as lawyers but will help to lead society in a manner that is technically competent as well as socially aware. This new kind of engineering system 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.

These engineering systems faculty and the students they produce will help the academy address the issues framed by Donald Kennedy in his insightful book *Academic Duty*<sup>3</sup>. In the final chapter, he asked, "Can the universities really make a difference with respect to the Big Problems facing us?" His list of challenges ranged 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 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 them. These professionals in the academy will help us to overcome the world of "two cultures" as that Snow<sup>4</sup> 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 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<sup>5</sup> 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 to focus on the kind of interdisciplinary work to produce these people, 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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<sup>1</sup> W. Clough et al. "The Engineer of 2020: Visions of Engineering in the New Century", National Academies Press, (2004)

<sup>2</sup> C. M. Vest, MIT Presidents report for AY 99/00, June 2000

<sup>3</sup> D. Kennedy, "Academic Duty", Stanford University Press, Stanford, CA (1997)

<sup>4</sup> C.P. Snow, "The Two Cultures", Cambridge University Press, Cambridge, UK (1993)

<sup>5</sup> L. Linden, personal communication, 2000