Historical Perspectives on Engineering Systems

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Thank you, it's an honor to speak to this distinguished group, and especially sandwiched between my teacher and colleague, Tom Hughes, and Dan Roos who brought me into engineering systems at MIT six years ago. I'm an electrical engineer and an historian of technology, so I both develop technologies and think about their broader implications. At MIT I teach the next generation of engineers to be both technically competent, and to be skilled in analyzing, synthesizing, and influencing the broader directions of technology. Like Tom, I'll use history as my guide to provide some broad perspective on Engineering Systems, and I'll also end with some thoughts about how we can educate engineers in new kinds of systems thinking.

I. Bush and circuits

I'll start with a familiar name, Vannevar Bush. Bush is of course well known at MIT, and throughout the world as the man who helped the country bring science to bear on World War II, and who initiated the Manhattan Project, and shaped post-war science policy in this country.

But there was a time when Bush was a young engineering faculty member, and in going through his publications one comes across some remarkable ideas. He wrote a book in 1929 called, *Operational Circuit Analysis* where he built on Oliver Heaviside's work to articulate an idea that is absolutely common in engineering schools today: that across hydraulics, mechanics, electricity, and acoustics, one finds the basic idea of the *circuit*. Bush and his students began to model one type of circuit with another, using small laboratory circuits, for example, to model large electric power systems. Once engineers realized that all "circuits" were similar, they understood that feedback, amplification, flow and a few basic mathematical operators could characterize engineering systems across a wide variety of engineering fields. This formed a critical early foundation for systems engineering.

[SLIDE: Vannever Bush and D.A.]

Bush's work emerged from the electric power industry, but by concentrating on circuits and modeling, he enabled engineers to move beyond consulting on industrial applications and to earn the prestige of scientists. When Karl Compton became president of MIT in 1930, he led the school to focus on “engineering science” and Bush’s work easily adapted. Which leads to my major point today: the distinction “engineering science” and “engineering systems” is a modern one – for systems approaches like Bush’s, were the ultimate in “engineering science” – a set of principles and mathematical tools that tied together all of engineering.

II. WWII Signals and noise

World War II coalesced this systems thinking in several arenas. In response to technical problems like radar and automatic gunfire control, the sense of systems as dynamic entities came to the fore. Electronics and mechanisms had to work together as never before, leading to the merger of servomechanism theory, communications theory, and feedback control. During the war, engineers began to use ideas of signals, noise, and frequency spectra, developed at Bell Labs by people like Harry Nyquist and Hendrik Bode, to conceptualize not just telephone signals, but all types machines and dynamics: from radar reflections to the motions of aircraft. They also recognized the ubiquity of feedback in electronics, hydraulics, servos, even human operators. This was Bush's approach writ large: if everything could be modeled as a circuit, then all systems were equivalent at some level. And, of course, you could build a machine to model them all: *a computer*.

III. OR, systems analysis, etc.

We find this trend throughout the war effort. As another example, Operations Research emerged as engineers and planners recognized the need to concentrate on the *operational* aspect of military systems, not simply on their *development*, and began to understand the entire war as a flow of materials, from the point of production to the point of "delivery" (i.e. the battlefield). In another vein, engineers began to use the word "integration" and to argue for a special organization to tie a large project together, setting the stage for the modern practice of systems integration.

[SLIDE: Ivan Getting & quote]

In the 1950s, engineering intellectuals absorbed and articulated the war's lesions. In the *Oxford English Dictionary* under the word *system*, you see uses of the term explode after 1950, *including systems engineering, systems analysis, systems dynamics, general systems theory*, and a host of others. Each field had its own innovators, its own emphasis, and its own home institutions and professions, but they shared common concerns with feedback, dynamics, flows, block diagrams, human-machine interaction, signals, simulation, and the exciting new possibilities of computers. At this point as well we begin to see textbooks with 'system engineering' in their titles.

[SLIDE: RIDENOUR BOOK]

The management aspects of systems engineering formalized in the mid 1950s when the Air Force stretched its resources to quickly build an intercontinental ballistic missile. Aircraft had always been composed of large numbers of components from a variety of subcontractors, coordinated by the prime contractor who built the airframe. With a project like Atlas, dynamics, interconnection, and coordination became the dominant aspects of the project, so airframe companies, with their emphasis on structures and manufacturing, lost their central role, in favor of systems integrators.

[SLIDE: RAMO and quote]

Simon Ramo and Dean Woolridge spun out of Hughes Aircraft to found a systems-engineering contractor that soon became known as TRW (it's worth noting that the T in TRW came from the automobile industry). Ramo had cut his teeth at GE and Hughes Aircraft, and Woolridge came out of Bell Labs. Ramo became a promoter of systems engineering, which he defined as "the design of the whole from the design of the parts." We can find other examples of similar type systems engineering and management through the 1950s – and Tom Hughes has written about these in his book *Rescuing Prometheus*. There's the SAGE air defense system, which focused on computing, information exchange, and servomechanism theory. The Polaris submarine project was organized around a "Special Projects Office" in the Navy that was doing what we would today call systems engineering.

A variety of intellectual movements arose as well. Jay Forrester's System Dynamics defined management "as designing and controlling an industrial system" and argued that an industrial system was fundamentally an "information feedback system" like a servomechanism. Norbert Wiener's *Cybernetics* argued that feedback control and statistics pervaded computers, organisms, social systems, even the mind itself. The RAND corporation developed techniques that became known as “systems analysis” to evaluate policy options.

Indeed we can identify a group of “systems sciences” that emerged during the decades after World War II, and many of the pioneers of those sciences were indeed the teachers of the people in this room. They shared a common set of assumptions about how various aspects of the world might be understood in abstract, quantitative terms, and modeled with a series of feedbacks, flows, dynamics. Computers, both analog and digital, figured prominently in the image and the practice of these systems sciences. Social systems could be modeled with similar techniques as the more technical systems.

Again, my basic point is that these systems sciences were not *opposed to “engineering science.”* Science was the high-prestige field of the day, and engineering schools hoped to emulate scientists to share some of that glory. Gordon Brown, a former student of Vannevar Bush became Dean of Engineering at MIT, and moved the school further toward the engineering science model, emphasizing physics-based, laboratory-driven work in education and research. Systems thinking was very much in this vein: an objective, authoritative scientific way to transcend “politics” with the outside neutrality of the expert.

This approach shaped the world in which many of us grew up – many faculty at MIT would call themselves engineering scientists, my own engineering education in the 1980s was shaped by engineering science, and engineering science is still going strong and will continue – for good reason, it has been enormously successful in solving the problems it defines for itself. Yet we understand that the problems of today's world will not be solved by new inventions or devices alone, but rather by large systems properly conceived, implemented, and managed -- this is what the new engineering systems is about. Hence we continue to revisit, appropriately, the old ongoing debate that ran throughout the twentieth century: What is the appropriate mix of "scientific" research versus industrial techniques a top engineering school?

IV. Systems Analysis and the Spread of the Systems Approach.

Now Tom Hughes showed how great engineers dealt with the "messy complexity" that arises within any large, technological project. Yet the systems techniques of the 1950s sought to eliminate uncertainty, *to reduce complexity to calculation*. Far from capturing a rich nuanced picture of the world, systems thinking after World War II often involved a top-down, hierarchical view of systems. This approach carried social implication as well: if the system could be *modeled*, then everything emanated from the *models*, and also from the *modelers* themselves.

During the 1960s, systems approaches faced their greatest defeat, and also their greatest triumph. When Robert McNamara entered the Pentagon in 1961, he brought systems analysis to national defense, modeling it as a single, large production system. McNamara's group of 'Whiz Kids' (many from MIT and RAND) modeled the 'production' of national defense as a series of inputs and outputs. Systems analysis helped empower the civilian leadership of DoD over the military services, but perhaps at the cost of their own perspective. As historian David Jardini writes, "through systems analysis, McNamara and his staff felt empowered to replace the complexity of real life with simplified models that were lent illusory precision by their quantitative bases." Indeed, McNamara's interest in systems approaches informed the quantitative modeling of warfare in Vietnam, and may well have contributed to the disaster there . For some, Vietnam proved the pitfalls of systems thinking when it was applied unthinkingly to a problem for which it was ill suited (although McNamara himself felt the problem was *not enough* systems thinking, rather than too much). By no coincidence did the student protesters of the 1960s refer to “the System” as the symbol of what was wrong with the world. If you’ve seen Errol Morriss’s recent movie *The Fog of War* there’s a nicely-done, disturbing scene where McNamara describes his modeling techniques, while the film shows the view from an aircraft dropping bombs on Vietnam; gradually the film fades to an eerie animation where the bombs change to numbers that fall down and explode.

Simultaneously with Vietnam, however, classical systems methods and systems engineering were achieving the great triumph of the moon landings. The Apollo project was run on a systems management model *par excellance*, and indeed many of the Apollo managers came from the Atlas program. NASA employed systems engineering to break down the project into smaller units, subcontract those units, manage the interfaces between them, and integrate them back into a whole. Apollo had the virtue of containing a clearly-defined goal, susceptible to a technical solution. Propulsion, guidance, and control dominated, as opposed to other systems where more complex social or network effects came to the fore. Even so, Apollo’s luxurious isolation proved to be short lived; the political consensus that supported it began to unravel even before the first landing in 1969. Despite its triumph, the project was canceled before it was finished.

During the 1960s and 70s, systems techniques, and frequently systems organizations themselves, were brought to bear on a variety of civil problems: urban poverty, mass transportation, health care, education and housing. Such attempts met with mixed results. Military organizations generally had more authority to effect solutions than did civil organizations; the civil problems tended to require more negotiation, compromise, and consultation than technically focused-military problems. In retrospect, the engineers would often point to the detrimental effects of politics, which stifled or derailed their projects. But in doing so they pointed to the limitations of their own models, which excluded politics and the social world as *external* variables.

Which brings me to my conclusion, at a kind of turning point in the early 1970s. A host of events began to force a slow rethinking of the systems approaches of the 50s and 60s.Vietnam. The cancellation of Apollo. The oil shocks. The Mansfield amendment. *The Limits to Growth*. The cancellation of the Super Sonic Transport. The invention of the microprocessor. All occurred within five years of the moon landing.

These and similar events began to lead engineers away from a narrowly technical definition of systems toward progress in more complex socio-technical systems – efficiency, economics, environmental impact, and, of course, information came to the fore. A great example is today's airliners, which go no faster than the first jets of 1960 – but speed is no longer how we measure progress. The airliners of today are far more sophisticated machines than they were forty years ago – in their control systems, propulsion, manufacturing, safety, maintainability, and numerous other systems. The measurements of progress are no longer strictly Newtonian, but are embedded in the industrial, social, and economic systems that surround the machines.

Dan Roos will show that this era saw the roots of the new "systems approach" that is embodied in the Engineering Systems Division. It would take decades, and require the crisis over competitiveness, the end of the Cold War, and a host of environmental and other events to get us to where we are now. We have learned in the last thirty years that technology develops in ways that are not always predictable, that complexity presents us with problems that we cannot yet handle analytically, and that politics and people are part of technology, not external to it.

So to conclude, what we are calling "engineering systems" and discussing for the next two days is not old-fashioned "systems engineering" – it does not treat politics and society as external variables to be excluded from the models, it does treat the models or the modelers as sacred, and it does not seek to educate engineers solely as scientists, but also as inventors, managers, and policymakers – in sum, as leaders.

To educate these engineers as the leaders of tomorrow, engineering schools must teach students how to deal with complexity in a rigorous but nuanced way. For me, history provides a way to capture, analyze, and convey an enormous mass of complex information about technology. But our students might choose political science, sociology, anthropology, or even literature to complement and complete their engineering expertise. It is highly significant that the Columbia Accident Investigation Board identified "history and culture" as a major contributing cause of the accident. History and culture are not mysterious, inhibiting forces that act on technological development; they are just as integral to technology as are Newton's laws and Fourier transforms. There are faculty on this campus and many others that are expert in understanding them, but too few of them are comfortable with machines, and many are outright suspicious of them. We must train engineers who are both intimate with technology (not only mathematics!) and who are great communicators, and scholars of history and culture. For those who can do both, great worlds lie open to them, and they will be positioned to make the major decisions that direct technology to improve our world.