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BODIES, IDEAS, AND DYNAMICS:
HISTORICAL PERSPECTIVES ON SYSTEMS
THINKING IN ENGINEERING

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I. Introduction

Today, the idea that technology consists not simply of individual machines but of systems of components and interconnections underlies much of engineering theory and practice. Yet this idea is relatively new in the history of technology; it evolved over a long period, spanning more than a century, as engineers grappled with the implications of machinery and collections of apparatus that spread over broad geographical areas. A historical perspective on systems thinking provides a critical background for contemplating new directions in “engineering systems,” by highlighting the problems that have constantly challenged engineers, as well as the new puzzles posed by today’s world.

This paper surveys the history of systems thinking in engineering in the United States, from the nineteenth century to the late twentieth. Throughout this period, engineers concentrated on certain kinds of technical systems and developed various modes of systems thinking to deal with them. Early in the 19th century, systems thinking developed as coherent philosophies in specialized areas like manufacturing and the military. Later in the century, the railroads emerged as a large-scale system with diverse flows and materials. From the late nineteenth century to World War II, systems thinking in the electric power and telephone industries focused on interconnecting disparate elements into larger wholes for systems spread over large geographic areas. World War II led engineers to conceptualize systems as integrated, dynamic entities, and to formalize methodologies for managing the complex organizations to design and operate such systems. These approaches flourished in the Cold War, although its techniques are still with us today in selected areas. Late in the twentieth century, engineers began to expand the boundaries of technical systems to include not only their internal or organizational dynamics, but also broader social and industrial contexts. Engineers now also recognize that the complexity of these systems means that accurate prediction or even simulation is not always possible.

A few caveats are in order. First, to focus the discussion, I'll discuss systems thinking primarily as it relates to engineering, and not in other arenas such as biology or economics. Second, I tend to focus on electrical technologies. Some have argued that electricity lends itself to systems thinking, forcing engineers to think in terms of circuits and flow.¹ Still, a similar story could be probably written about other endeavors like the chemical process industries. As a third qualification, for brevity I focus on the United States, but not to imply that American developments were first or primary; similar stories occurred in other countries as well. Finally, this paper cannot be comprehensive, but rather aims to point out some significant moments in a vast, complex story over a long period of time.

II. Re: "System"

After World War II, systems thinking diffused from engineering into a variety of disciplines, including the history of technology itself. Leading this endeavor has been Thomas P. Hughes, whose work covers a broad range of topics and periods. Hughes's work and his insights provide a foundation for an historical understanding of systems.² This essay, however, differs from Hughes in critical respects. Hughes's work had two goals: first, to delineate historical moments of thinking about systems, such as in electric power or air defense. His second goal is a model of technological change, which has come to be known as the "systems approach." Hughes himself was influenced by systems thinkers like Wiener and von Bertalanffy, and his writings sought to develop a systems model of technological change that is unchanging.

By contrast, here I seek to delineate a variety of meanings for "system." Beginning with early uses of the term, I show it has various meanings, and examine how it developed differently in a number of discrete environments.³ Rather than seeking an overarching systems model of historical change, my goal here is an historical epistemology, tracing the history of systems thinking and its meanings. I borrow Walter Vincenti's idea of engineering epistemology, which

¹ Thomas P. Hughes, *American Genesis: A Century of Invention and Technological Enthusiasm* (New York: Penguin, 1989), 186.

² Wiebe E. Bijker, Thomas Parke Hughes, and Trevor J. Pinch, eds., *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology* (Cambridge: MIT Press); *Networks of Power: Electrification in Western Society, 1180-1930* (Baltimore: Johns Hopkins, 1983); *American Genesis*. For the connections between Hughes and Chandler, see David Hounshell, "Hughesian History of Technology and Chandlerian Business History: Parallels, Departures, and Critics," *History and Technology* 12 (1995) 205-224.

³ Here I echo Raymond Williams's approach from *Keywords* where he traced a number of words that seem to define the modern world, like "communication," "bureaucracy" and "revolution," according to their historical usages. Curiously, *Keywords* contains no entry for "system" or "technology." (New York: Oxford University Press, 1976).

he elegantly defined as “what engineers know and how they know it.”⁴ The goal is to outline what engineers knew (and thought, and said) about systems and how they knew it. Of course engineering knowledge consists of much more than textbooks or published papers. Each type of systems thinking accompanied characteristic technologies, institutions, and intellectual tools. Of particular interest is the level of self-consciousness on the part of engineers: whether they were engaging in something that today would we call systems thinking, or whether (and how) they used the term “system” itself. What, for example, did Bell Labs mean by “System Engineer” in the 1920s? When, for example did the term “system engineering” arise? Comparing engineering theory and practice along these axes over a broad span of time reveals both the changing nature of systems thinking as well as those elements that remained constant.

By *systems thinking* I mean the practice of treating technologies as aggregates of interconnected components, as opposed to focusing on individual machines. Such components may involve both organizational and mechanical elements, humans and non-humans. This is not to imply, however, that the idea of “system” has some stable essence that remains fixed over time. A system can be defined by the components themselves, or by the connections, or by their behavior as a group. Sometimes it can be broken down into smaller subsystems for analysis, other times it be analyzed only as a whole. Some system builders think about aggregates, others see the world in terms of flow, or feedback, or emergence. These views varied over time, depending on technical and historical circumstances.

Complicating the problem is the broad array of uses and techniques associated with the word “system,” making it difficult to discern any unifying, or even common elements. One way to sort through the complexity, then, is to begin with the word itself – and to pay attention to how, and whether, engineers and technologists used the word. The word’s history provides a useful framework for distinguishing and relating the variety of systems approaches.

Before the 19th century the word *system* had little technological or mechanical meaning at all. The *Oxford English Dictionary* (OED) lists hundreds of examples of historical usage for *system*, but before the mid-nineteenth century they refer to machinery only rarely. After about 1830, the OED shows that people began to use *system* for technological objects, and the word appeared in a few selected areas for the next hundred or so years. After 1950, *system-* terms

⁴ Walter Vincenti, *What Engineers Know and How they Know It: Analytical Studies from Aeronautical History*

explode, reflecting the self-consciousness of post-war systems thinking. Still, the word's early history provides three useful categories for understanding its technological meanings:

Physiological systems – elements linked in networks or trees, containing flows; early examples include the nervous or circulatory systems in the body.

Systems of philosophy – coherent sets of ideas; early examples include legal systems, or Adam Smith's description of the "Capitalist system" in the *Wealth of Nations* as a method of organizing trade and exchange.

Dynamic systems – sets of interacting physical units; early examples include the universe or the solar system. As natural philosopher William Paley wrote in 1802, "The universe itself is a system; each part either depending upon other parts, or being connected with other parts by some common law of motion."⁵

Though these three categories refer to non-technological uses of "system", they help distinguish among the wide variety of systems terms that appear after the industrial revolution.⁶ Examples of physiological systems today include large technological systems that spread over broad areas. Today we find systems of philosophy in management techniques, and systematic approaches to problem solving. Modern examples of dynamic systems include feedback controls, network simulations, or complex adaptive systems.

III. The Nineteenth Century

By the 1850s, railroads had become an inescapable part of the American landscape, yet they were poorly captured by the term "machine." In general, the language of traditional "mechanical arts" proved increasingly inadequate to describe changes in the technological world. Railroads not only physically spread their rails across the land, but also encompassed a host of

(Baltimore, Johns Hopkins, 1990), 3-15.

⁵ Paley, *Natural Theology* XXV (1819) 398, quoted in *Oxford English Dictionary*, entry "system," definition I.1.a.

bridges, tunnels, signals, capital, a skilled workforce, and a new corps of people called managers. Railroads shared some of these features with the roads or postal networks that preceded them, but added steam-power, complex machinery, and problems of real-time coordination to prevent collisions. In 1828, Jacob Bigelow revived an old term to capture the complexity of the new enterprise and others like it: *technology*.⁷ Though the word did not enter common use for a long time, its appearance was not coincidental. The very notion of *technology* is closely linked, both conceptually and historically, to the notion of *system*. Both ideas draw attention to the numerous components of new phenomena like railroads, beyond simply the machines, and both imply a blurring of the boundaries between machine operation and human organization, between engineering and management.

In response to these and similar situations posed by the railroads, modern management emerged as a what Alfred Chandler called the “visible hand” to replace invisible market mechanisms with human coordination and control. Chandler describes the rise of modern management using the physiological sense of system, referring to “the functions of coordinating flows of goods through existing processes of production and distribution.”⁸ Indeed the tools for communication and coordination could not be separated from those of moving the goods themselves, as Chandler writes, “the railroad and the telegraph moved across the continent in unison.”⁹ According to Chandler, managers and engineers clearly saw their railroads in terms of communications, flows, and interactions. They even built up national “systems” of main lines and local and regional feeders – all coordinated by centralized management structures, including significant data collection and statistical departments.¹⁰ Late in the century, this information process became mechanized. Punch-card innovator Herman Hollerith, in fact, explicitly made the analogy between information flows in his machines and railroad switchyards. Nor were the systems of flows limited to the railroads themselves. In Chicago, for example, the introduction of telegraphy, railroads, and grain elevators in the decades before the Civil War enabled farm

⁶ Ludwig von Bertalanffy makes a somewhat similar set of distinctions: systems technology, systems philosophy, and systems science. He also distinguishes between types of systems: real, conceptual, and abstracted. See “Preface to the Revised Edition,” *General System Theory* (New York: George Braziller, 1969).

⁷ Leo Marx, 1997, “Technology: The Emergence of a Hazardous Concept,” *Social Research* 64 (No. 3, fall) 966:88.

⁸ Alfred D. Chandler, *The Visible Hand: The Managerial Revolution in American Business* (Cambridge, Mass.: Harvard University Press, 1977), 1. James R. Beniger, *The Control Revolution: Technological and Economic Origins of the Information Society*, (Cambridge: Harvard University Press, 1986).

⁹ Chandler, *The Visible Hand*., 195.

¹⁰ *Ibid.*, 98-99, Chapter 5.

products to flow as “golden stream,” creating, in the words of historian William Cronon, “a new market geography that had less to do with the soils or climate of a given locality than with the prices and information flows of the economy as a whole.”¹¹

Other nineteenth century technologists and managers used *system* in its philosophical sense. In 1854, the inventor John Ericsson, who would later build the ironclad *Monitor*, wrote of a “new system of naval attack,” by which he meant not a system of flows like the railroads, but a philosophy of mechanized warfare. That same year, British observers to the United States dubbed the “American system” the manufacturing techniques involving heavy mechanization and interchangeable parts, found at the Springfield armory and other machine shops.¹² This “system” referred to the overarching philosophy rather than flows of parts through workers and machines. Even in 1911, when management consultant Frederick Winslow Taylor famously quipped that “in the past, the man was first, in the future, the system must be first,” he referred to his system of Scientific Management, not to the physical components of the production system. Indeed Taylor focused on designing optimal human behaviors for a given task, more than redesigning the task itself within larger flows and networks. His work built on the “systematic management” movement that had grown up around the railroads – emphasizing standardized tasks and forms as ways of unifying an organization.¹³ Henry Ford clearly conceptualized his famous assembly line factories in terms of flows of parts and products, but he used the metaphor of the machine– a well-oiled set of tightly coupled parts – rather than “system.” In sum, engineers’ in the nineteenth century ended to use “system” in the physiological or philosophical senses, but without making direct analogies between the two.

¹¹ William Cronon, *Nature’s Metropolis: Chicago and the Great West* (New York: Norton, 1991), Chapter 3.

¹² David A. Hounshell, *From the American System to Mass Production, 1800-1932: The Development of Manufacturing Technology in the United States* (Baltimore: Johns Hopkins University Press, 1984): Hounshell (pp. 331-35) has an excellent usage history of the term “American system of manufacturing,” covering 1851-1937 that fills in much of the period missing in the OED. According to Hounshell, the common, repeated use of the term “American system” really dates from the 1880s, but the term “systems” was often used to describe the sum of techniques used in manufacturing. Merritt Roe Smith, “Army Ordnance and the “American System” of Manufacturing, 1815-1861,” in idem. ed., *Military Enterprise and Technological Change*, 39-86. On Ericsson’s “system of naval attack,” see David Mindell, *War, Technology, and Experience Aboard the USS Monitor* (Baltimore: Johns Hopkins University Press, 2000), 121.

¹³ Frederick Winslow Taylor, *The Principles of Scientific Management* (New York: Harper & Brothers, 1911) p. 7. Daniel Nelson, *Frederick W. Taylor and the Rise of Scientific Management* (Madison: University of Wisconsin Press, 1980). Hughes, *American Genesis*, Chapter 5. JoAnne Yates, *Control Through Communication: The Rise of System in American Management* (Baltimore, Johns Hopkins University Press, 1989), 9-15. Beniger, *The Control Revolution*.

Edison and electric power

Echoing the pattern of the railroads, electric power grew up on a similar model, though more consciously planned as systems. Thomas Edison is hailed as a genius inventor for creating the light bulb, and indeed the light bulb has become a symbol for invention. But Edison's electric light succeeded because he designed not only light bulbs, but also a system that included generators and transmission lines. When developing his system in the late 1870s, Edison explicitly compared it to the competitor he intended to replace: gas lighting. Edison designed light fixtures to resemble gaslights. An economic analysis of the cost basis of electric versus gas lighting led him to concentrate on a high-resistance filament, which required less current and hence smaller transmission lines than the lower resistance model his rivals were pursuing. Edison described his invention in the physiological sense, as connected elements with current flowing between them. It was, in his words, "a system based on different inventions or discoveries, some of which have been made years before the others."¹⁴ Edison also organized invention in the philosophical sense, initiating many of the features of a modern industrial R&D laboratory, especially an organization devoted to a "systematic" attack on technical problems.

During design, Edison clearly understood how the components of his electric lighting system interacted with each other. He was less clear, however, on the dynamics of the system, or how those relationships affected each other during operations.¹⁵ Indeed, Edison's early systems had stability problems, which his engineers solved with cut and try methods, not according to any overall model of their dynamics. For example, when the generators at the Pearl Street Station began to oscillate, the only solution was to replace them with newer ones, not to detune the system to avoid the resonance.¹⁶ This approach worked well when the systems were simple, and even up to moderate size, and up through the 1920s, engineers conceptualized electric power systems in the physiological sense, as sets of interconnected elements like generators, motors, traction loads, or transmission lines, each of which could be designed and analyzed independently and then combined. As local networks, engineers could treat them as hierarchical and centrally controlled, with all power emanating from a central station.

¹⁴ Edison to Butler, February 1879, quoted in Paul Israel, 1998. *Edison: A Life of Invention* (New York: Wiley), 189.

¹⁵ Hughes, *Networks of Power*, 31.

¹⁶ Nathan Cohen, "Recollections of the Evolution of Realtime Control Applications to Electric Power Systems," *Automatica* 20 (2, 1984), 145-62.

As alternating current replaced Edison's DC system, engineers began to focus more on the interactions between the components, and began articulating their dynamics. Engineers like Charles Proteus Steinmetz at General Electric studied the precise, quantitative relationships between elements in electrical systems, both in steady state and transient modes. At the same time, the growing size of the electric power industry allowed a formalization of Edison's laboratory. Around 1900 Steinmetz spurred G.E. to open corporate research laboratory, separate from the daily business of the company. The GE Lab focused mostly on chemistry and manufacturing issues, but Steinmetz's work exemplified how the separate, academically-oriented sphere enabled engineers to conceptualize the system in broader, more abstract terms than they would in an operating unit or a product design department.¹⁷

In the 1920s, local or regional power networks connected into national "grids" or "superpower" systems. Hughes has pointed out the importance of "load factor," as electric power systems expanded to equalize their average and peak demand.¹⁸ No longer could individual systems be considered only as the power emanating from the station in the center of town. Now a system might incorporate a varied residential and industrial loads, coal-fired plant, and a hydroelectric station miles away – and connect to similar networks over a long transmission and tie lines. These new networks began to exhibit behaviors that could only be understood by looking at the system as a whole.¹⁹ Stability problems with large, interregional electric power networks drove engineers to study the characteristics of large-scale power networks as complete entities, and to conceptualize them as systems in the dynamic sense.

This new approach was exemplified by a young electrical engineering professor at MIT, Vannevar Bush, who sought to bring a variety of systems under a single quantitative model. In his 1929 book, *Operational Circuit Analysis* Bush applied Heaviside's operational calculus to model systems of varying types. Bush noted that across fields in engineering like hydraulics,

¹⁷ Ronald Kline, *Steinmetz: Engineer and Socialist* (Baltimore: Johns Hopkins University Press, 1992). Hughes, *American Genesis*, 161-175. While Steinmetz had the vision, G.E.'s research laboratory was headed by Willis R. Whitney, a chemist, and focused primarily on physical chemical problems related to electric lighting.

¹⁸ Hughes, *Networks of Power*, 218-21.

¹⁹ See Committee on Power Transmission and Distribution, "Annual Report," *Trans. A.I.E.E.* 46 (June, 1927). For a general review of the subject of power system stability, see C.L. Fortescue, "Transmission Stability: Analytical Discussion of Some Factors Entering into the Problem," *Trans. A.I.E.E.* 26 (February, 1927), 984-994 and discussion 994-1003. Frederick Terman, "The Characteristics and Stability of Transmission Systems" (Sc.D. diss., MIT, 1924). Vannevar Bush, "Power System Transients," *AIEE Trans.* 44 (1925), 229-30. C. L. Fortescue, discussion of Bush and Booth, "Power System Transients," *Trans. AIEE* 44 (February, 1925), 97-103. This discussion, from six commentators, provides a good overview of the state of the stability problem in 1925.

mechanics, electricity, and acoustics, one finds the basic idea of the *circuit*, defined as “a physical entity in which varying magnitudes can be sufficiently specified in terms of time and a single dimension.”²⁰ This project treated engineering systems as abstractions, and allowed engineers to work with analogies between them – especially to solve power system stability problems. Indeed Bush’s students, like Harold Hazen, King Gould, Gordon Brown, and others began to build “network models” (what we would today call simulators) and calculating machines to model complex systems with smaller, laboratory based devices. By no coincidence did this work lead in the 1930s to contributions in calculating machines and servomechanisms – with the proposition that all circuits were similar came the recognition that basic ideas like feedback, amplification, flow and a few basic mathematical operations could characterize linear systems across a wide variety of engineering fields.²¹ Put another way, one could study related systems because of the analogies between their physical dynamics. Again, the organizational conditions of research were related to the emerging view of systems. As engineering schools like MIT began to focus on “engineering science” after 1930, simulation and mathematical modeling provided general, high-level techniques that enabled engineers to move beyond consulting on industrial applications and to earn the prestige of scientists.²²

III.A. Telephone

In the other new large technical system of the early twentieth century, the telephone network, engineers used the language of systems more explicitly than in electric power. AT&T chief Theodore Vail’s famous motto “One policy, one system, universal service,” captured the company’s totalizing view, though its network was composed of vast numbers of small, interconnected units. Within AT&T, engineers referred to their national network as “the System,” and beginning in the 1920s the company had job titles for “System Engineers” and a “Systems Development” department. Yet these were not systems engineers in the modern sense;

²⁰ Vannevar Bush *Operational Circuit Analysis* (New York: J. Wiley & Sons Inc.: 1929), 1-2. John Carson, *Electric Circuit Theory and the Operational Calculus* (New York: McGraw-Hill: 1926).

²¹ For more detail, see David Mindell, *Between Human and Machine: Feedback, Control, and Computing Before Cybernetics* (Baltimore: Johns Hopkins: 2002), Chapter 5.

²² Bernard Carlson, “Academic Entrepreneurship and Engineering Education,” and Alex Soojunk-Kim Pang, “Edward Bowles and radio engineering at MIT, 1920-1940,” *Hist. Stud. Phys. Bio. Sciences* 20 (no. 2, 199), 313-337. Christian Lecuyer, “The making of a science based technological university: Karl Compton, James Killian, and the Reform of MIT, 1930-1957,” *Historical Studies in the Physical Sciences* 23 (1), 1992, 153-80. Larry Owens, “MIT and the Federal ‘Angel:’ Academic R&D and Federal-Private Cooperation Before World War II,” *Isis* 81

they did not have an abstract view of the system, nor did they manage a variety of subsystems. Rather, system engineers at AT&T concentrated on the concrete manifestations of the networks: the equipment layouts, power systems, and wiring diagrams for local substations.²³ The system was physiological, a thing, emanating from central switching stations.

As in electric power, the growing size of the national telephone network spurred the company to create a new organization. Bell Telephone Laboratories was founded in 1925 to focus on developing repeater amplifiers, which would allow the network to continue to grow arbitrarily large. Only a small part of Bell Labs concentrated on fundamental problems like those university researchers would address; rather, like Edison had done, they sought “systematized research,” or a coordinated attack on a set of industrial problems.²⁴ Still, engineers at Bell Labs were freed from the daily concerns of the system and protected by AT&T’s monopoly. An increasing number were trained with Ph.D.s and began to study the system as a dynamic entity.

The *Bell System Technical Journal* of the 1920s and 30s is replete with articles on topics like the statistics of switching, the interchangeability of bandwidth, and the economics of the network. Through innovations like Bode and Nyquist’s work on the stability of feedback amplifiers, as well as Nyquist’s and Hartley’s work on transmission channels, engineers gradually began to formulate the system in abstract terms. The telephone network could be seen not simply as a set of wires delivering telephone conversations, but as a set of transmission channels able to convey any type of information through a finite bandwidth.²⁵ As Bell Labs founder Frank Jewett told the National Academy of Sciences in 1935, “We are prone to think and, what is worse, to act in terms of telegraphy, telephony, radio broadcasting, telephotography, or television, as though they were things apart. When they are merely variant parts of a common applied science. One and all, they depend for the functioning and utility on the transmission to a distance of some form of electrical energy whose proper manipulation makes possible

(1990), 188-213. John W. Servos, “The Industrial Relations of Science: Chemical Engineering at MIT, 1900-1939,” *Isis* 71 (1980): 531-49.

²³ “The Systems Development Department.” *Bell Lab. Rec.*, April 1926, 69-73.

²⁴ Harold D. Arnold, “Systematized Research.” *Bell Lab. Rec.*, June 1928, 316-17. Paul B. Findley “The Systems Development Department.” *Bell Lab. Rec.*, April 1926, 69-73. Leonard Reich, *The Making of American Industrial Research: Science and Business at GE and Bell, 1876-1926* (Cambridge: Cambridge University Press, 1985).

²⁵ David A. Mindell, “Opening Black’s Box: Rethinking Feedback’s Myth of Origin,” *Technology and Culture*, July, 2000. Harold Black “Stabilized Feedback Amplifiers.” *Bell Sys. Tech. Jour.* (1934): 1-18. Harry Nyquist “Certain Factors Affecting Telegraph Speed.” *Bell Sys. Tech. Jour.* 3, April (1924): 324 :46; “Certain Topics in Telegraph Transmission Theory.” *Trans. AIEE* 47, February (1928): 617-44; “Regeneration Theory.” *Bell Sys. Tech. Jour.* 11 (1932): 126-47.

substantially instantaneous transfer of intelligence.”²⁶ Defining a technical language of signals was analogous to Bush’s use of the circuit – it provided a common set of dynamics to model a variety of flows.

IV. World War II and the systems era

World War II coalesced 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. Engineers now conceptualized their machines as integrated systems with feedbacks and dynamics, where the behavior of each part helped determine the behavior of the whole. Quantitative techniques arose from the merger of servomechanism theory, communications theory, and feedback control. Before the war, telephone engineers dealt with voice signals by analyzing them in the frequency domain, an approach that Bode and Nyquist then brought to feedback amplifiers. During the war, engineers began to use ideas of signals, noise, and frequencies to conceptualize a variety of dynamics: from radar reflections to the motions of aircraft. Most important, they also recognized that feedback and its dynamics were isomorphic across a variety of systems, from electronics to hydraulic and electric servos to the role of the human operator.

Others conceptualized the broad flows of material and information that comprised the war effort as itself a system, in the physiological sense. 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 effort as a flow of materials, from the point of production to the point of “delivery” (i.e. the battlefield).²⁷ Like the railroads, such systems of flow were tied together by human organizations to gather and process information. Information technologies, from punched-cards to digital computers, facilitated these processes, and systems approaches and computing intertwined in a symbiotic evolution. Gradually, the management sense of “system” as a philosophy and the engineering sense of dynamic systems began to merge. Engineers began to use the term “integrated” to

²⁶ Frank B. Jewett, “Electrical Communication, Past, Present, and Future,” Speech to the National Academy of Sciences April, 1935, reprinted in *Bell Telephone Quarterly* 14 (July, 1935): 167-99.

²⁷ Eric Rau, “The Adoption of Operations Research in the United States during World War II,” in Thomas P. Hughes and Agatha C. Hughes, eds., *Systems, Experts, and Computers: The Systems Approach in Management and Engineering in World War II and After* (Cambridge: MIT Press, 2000). M. Fortun and S.S. Schweber, “Scientists

describe their systems. They defined a role for a coordinating organization to have technical oversight and management authority to “integrate” the entire project.²⁸

By 1950, these ideas and techniques began the self-conscious era of systems thinking. As mentioned above, the *Oxford English Dictionary* shows that the term *system* exploded 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.

Consider, as an example, systems engineering. Among the first texts to use the term was Louis Ridenour’s *Radar System Engineering*, published in 1947 as part of the Radiation Laboratory’s series of textbooks.²⁹ The title refers to the physiological sense of system, that is “how to engineer a radar system,” – where an individual radar is a connected set of components like magnetrons, waveguides, power supplies, and display tubes. Title does not refer to the philosophical sense of system, as in “how to system engineer a radar,” but such ideas are nascent in the book: it covers not only wave propagation and noise models, but also the appropriate design of displays and the dissemination of information through a radar organization. Ridenour’s text includes no discussion of feedback or servomechanisms, or of the dynamic characteristics of radar systems. A McGraw Hill text, *System Engineering*, published ten years later, included probability, analog and digital computers for simulation, queuing theory, game theory, information theory, servomechanism theory, and sections on “human engineering,” management, and economics.³⁰

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. In the Atlas project, management began to move beyond the model that had dominated the aviation industry

and the Legacy of World War II: The Case of Operations Research (OR),” *Social Studies of Science* 23 (November 1993): 595-642.

²⁸ David Mindell, “Automation’s Finest Hour: Radar and System Integration in World War II,” in Hughes and Hughes, eds., *Systems Experts and Computers*.

²⁹ Louis B. Ridenour, *Radar System Engineering. Radiation Laboratory Series vol. 1*. (New York: McGraw Hill, 1948).

³⁰ Harry Goode, and Robert Machol, *Systems Engineering: An Introduction to the Design of Large-scale Systems*. (New York: McGraw Hill, 1947).

for decades. 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. Rather, engineers with management experience, mathematical abstraction, and an understanding of dynamics and control coordinated the project. Simon Ramo and Dean Woolridge spun out of Hughes Aircraft corporation to found a systems-engineering contractor that soon became TRW. Ramo had cut his teeth at GE and Hughes Aircraft, and Woolridge came out of Bell Labs. Together with the Air Force's Western Development Division, they coordinated contractors and scheduling and oversaw the project's integration (in the Navy's Polaris project, the Special Projects Office performed a similar function).³¹ Ramo became a promoter of systems engineering, which he defined as "the design of the whole from the design of the parts." As Ramo wrote, "Systems engineering is inherently interdisciplinary because its function is to integrate the specialized separate pieces of a complex of apparatus and people – the system – into a harmonious ensemble that optimally achieves the desired end."³² Atlas included a physiological system of materials, logistics, computers and ground support, but once the missile launched it functioned as a dynamic system, independent of the larger network. Still, in Atlas, the philosophical sense of "system" dominated: the management expertise required for coordination.

SAGE, by contrast, created a distributed, real-time system that, like the telephone network, depended on information exchange and transmission during operations. SAGE was a continental air defense system that tied a series of radar tracking stations into a network of digital computers and command stations across the continent. The project emerged in the early 1950s from the Whirlwind digital computer built by MIT's Servomechanisms Laboratory. SAGE brought age-old problems of fire control into the world of digital electronics, information processing, and national systems. It also spawned a host of new systems-oriented organizations like MIT's Lincoln Laboratory and the MITRE Corporation. MITRE was founded to do systems engineering for SAGE, but with greater emphasis on coordination of subsystems than actual

³¹ Harvey Sapolsky, *The Polaris System Development: Bureaucratic and Programmatic Success in Government* (Cambridge: Harvard University Press, 1972)). Benjamin Pinney, "Projects, Management, and Protean Times: Engineering Enterprise in the United States, 1870-1960," (Ph.D. diss., MIT, 2001).

management of contracts. SAGE's designers saw the system as an "organism," by which they meant a high-organized, coordinated system of units coordinating together toward a particular purpose.³³ The notions of systems embodied in SAGE were physiological and dynamic: everything working in concert, a geographically distributed network of humans and machines under yoked to the will of a small number of military commanders. Embedded in this project was the idea that these large, geographically diverse systems might themselves have dynamics akin to smaller, more integrated counterparts. Indeed one Air Force colonel called SAGE "a servomechanism spread over an area comparable to the whole American Continent."³⁴

In Atlas and SAGE, systems engineering meant coordinating and controlling a variety of technical and organizational elements, from contract specifications to control systems, from computer simulations to deployment logistics. For the strategy to work, the system engineer required a certain amount of authority, a fact that was not lost on the participants. For its practitioners, systems thinking was objective, authoritative scientific way to transcend "politics" (whether public or military-industrial) with the outside neutrality of the expert. Still, the comparison between Atlas and SAGE illustrates the complexity and diversity already emerging within the systems sciences: one concentrated on management techniques for coordinating flows of materials and knowledge, the other focusing on a system as a concrete, dynamic entity spread over a large area.

One of SAGE's offshoots illustrates the dynamic view of systems it embodied: Jay Forrester developed Systems Dynamics as an adaptation of servomechanism theory for modeling other types of systems, beginning with industrial and moving toward urban and policy settings. Forrester defined management "as designing and controlling an industrial system" and argued that an industrial system was fundamentally an "information feedback system" like a servomechanism. The idea was that an understanding of a systems' dynamics could move from feedback systems in engineering to broader domains, facilitated by the advent of computers as

³² For a history of systems thinking in the Atlas project, see Hughes, *Rescuing Prometheus* (New York: Pantheon Books, 1998), Chapter III. Simon Ramo is quoted on page 67.

³³ Kent C. Redmond, and Thomas M. Smith. *From Whirlwind to MITRE: The R&D Story of the Sage Air Defense Computer* (Cambridge: MIT Press, 2000); *Project Whirlwind: The History of a Pioneer Computer* (Bedford, Mass.: DEC Press, 1980). George E. Valley, "How the Sage Development Began." *Annals of the History of Computing* 7, no. 3, July (1985): 196-226. Paul Edwards *The Closed World: Computers and the Politics of Discourse in Cold War America* (Cambridge: MIT Press, 1996). Hughes, *Rescuing Prometheus*, Chapter II.

³⁴ Quoted in Joseph Weizenbaum, *Computer Power and Human Reason* (New York: Freeman, 1976), 30.

simulation tools.³⁵ Norbert Wiener's *Cybernetics* made a similar move, arguing that the feedback control and statistics could evoke the analogies between the dynamics of computers, organisms, social systems, even the mind itself and find applications in a variety of the social sciences.³⁶

These approaches were diverse enough that precisely characterizing them is outside the scope of this paper. They did, however, share 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. They could simulate systems and make predictions about the system's behavior in an uncertain environment. Social systems could be modeled with similar techniques as technical systems. Both the computer, and the analysts themselves carried the prestige and authority of science: providing dispassionate, expert advice free of political influence.

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

Hughes argues that systems techniques were developed by engineers to deal with the “messy complexity” that arises within any large, technological project. Yet these early, formalized systems techniques were explicitly designed to eliminate uncertainty, to reduce complexity to calculation. Far from capturing a rich nuanced picture of the world, systems thinking often involved a top-down, hierarchical view of systems, with an accompanying political structure. If the system could be modeled, then everything emanated from the models, and from the modelers.

The RAND corporation, for example, developed techniques that became known as “systems analysis” to evaluate policy options. Systems analysis mixed quantitative and probabilistic techniques like operations research, game theory, probability and statistics, econometrics, and linear/dynamic programming. Extending the “war as a production system” view of OR during the war, RAND focused on developing a science of warfare: bringing quantitative certainty to one of humankind's most chaotic endeavors. In their classic *The Economics of Defense in the*

³⁵ Jay W. Forrester, *Industrial Dynamics*. (MIT Press, Cambridge, MA, 1961). *Urban Dynamics* (Pegasus Communications, Waltham, Mass., 1961).

³⁶ Norbert Wiener, *Cybernetics: or, Control and Communication in the Animal and the Machine* (Cambridge: Technology press, 1948). Steve J. Heims, *Constructing a Social Science for Postwar America: The Cybernetics Group, 1946-1953*. (Cambridge: MIT Press, 1993). Vyacheslav Gerovitch. *From Newspeak to Cyberspeak: A History of Soviet Cybernetics* (Cambridge: MIT Press, 2002).

Nuclear Age, Charles Hitch and Roland McKean stated their philosophical move from economics and management to military strategy: “the problem of combining limited quantities of missiles, crews, bases and maintenance facilities to ‘produce’ a strategic airforce that will maximize deterrence of enemy attack is just as much a problem in economics...as the problem of combining limited quantities of coke, iron ore, scrap, blast furnaces, and mill facilities to produce steel in such a way as to maximize profits.”³⁷ If war is a series of flows, of materials, information, even deterrence and destruction, then it can be planned with the techniques developed for analyzing flows of materials in industry – and optimized for efficiency and cost.

In a similar vein, 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. McNamara introduced, for example, the Planning-Programming-Budgeting-System (PPBS), originally developed at RAND in the 1950s, to overhaul budgeting practices within the Defense Department. He also established the Office of Systems Analysis at the Pentagon and used systems analysis as an aid in decision-making on weapon development and budgeting. 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.”³⁸ Indeed, McNamara’s interest in systems approaches also informed the quantitative modeling of warfare in Vietnam, and may well have contributed to the disaster there.³⁹ For some, Vietnam proved the pitfalls of systems thinking when it was applied unthinkingly to a problem for which it was ill suited. By no coincidence did the student protesters of the 1960s refer to “the System” as the symbol of what was wrong with the world.

Systems experts developed great confidence in the power of quantitative methods to incorporate and overcome numerous types of complexity, a confidence that spurred attempts to

³⁷ Hitch and McKean, *The Economics of Defense in the Nuclear Age* quoted in David Jardini, “Out of the Blue Yonder: The Transfer of Systems Thinking from the Pentagon to the Great Society, 1961-1965,” in Hughes and Hughes, eds., *Systems, Experts and Computers*, 311-57. Also see Roger Levien, “Rand, IIASA, and the Conduct of Systems Analysis,” in the same volume: 433-61.

³⁸ Jardini, “Out of the Blue Yonder,” 326-7, 342.

³⁹ Paul Edwards, *The Closed World: Computers and The Politics of Discourse in Cold War America* (Cambridge: MIT Press, 1996), Chapter 4.

apply systems methods to a variety of problems outside of engineering. 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 systems, health care, education and housing. Such attempts met with mixed results. Military organizations generally had more authority to effect solutions in their given sphere than did civil organizations, and the civil problems tended to require more negotiation, compromise, and consultation than technically focused-military problems did during the crisis atmosphere of the Cold War.⁴⁰ In the words of TRW's historian, "in many 'civil systems' ventures TRW personnel quickly abandoned the systems approach and embraced ways of managing appropriate to the industry."⁴¹ Systems analysts pointed to the detrimental effects of politics in stifling their projects, but in doing so pointed to the limitations of their models, which excluded politics as an external variable.

During the 1950s, a host of new disciplines appeared that we might call the systems sciences, including cybernetics, operations research, general systems theory, systems analysis, and systems dynamics – each had its own techniques, and unique character. All viewed the world in terms of flows, feedbacks, and interactions, and analyzed systems by breaking them down into component parts, understanding the characteristics of those parts, and then recombining them. These approaches were considered "engineering science," wherein expert analysis brought objective, quantitative analysis to complex problems, from nuclear targeting to procurement contracts.

The Cold War systems sciences achieved great success, particularly in areas with clearly defined technical goals. Apollo was the apotheosis of systems techniques in the 1960s. NASA employed systems engineering (borrowed from the Atlas program) 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 being a clearly-defined goal, one susceptible to a technical solution.⁴² It also was significantly determined by the dynamics of the system: issues of propulsion, guidance, and control dominated, as opposed to other systems where physiological or network effects came to the fore. Systems engineering of course became an established

⁴⁰ Davis Dyer, "The Limits of Technology Transfer: Civil Systems at TRW, 1965-1975," in Hughes and Hughes, eds., *Systems, Experts, and Computers*: 359-84.

⁴¹ Dyer, "Limits of Technology Transfer," 378.

⁴² For a good account of how NASA's systems engineering was transferred from Atlas and implemented in Apollo, see Thomas J. Kelly, *Moon Lander: How we Developed the Apollo Lunar Module* (Washington: Smithsonian Institution Press), esp. pages 42-47. Also see Stephen Johnson, *The Secret of Apollo: Systems Management in*

technique in engineering, valuable for product development and managing large projects, a field still generating a host of research and publications.⁴³ The systems sciences reached their limits, however, in Vietnam, the Great Society programs, and other civil systems with complex interactions, heavy political components, and vaguely defined boundaries.

American and European Space Programs (Baltimore: Johns Hopkins University Press, 2002). Richard Chapman, *Project Management in NASA: The System and the Men* (Washington: NASA, 1973).

⁴³ See, for example, Mark W. Maier and Eberhardt Rechtin, *The Art of Systems Architecting*, (CRC Press:, Boca Raton, Florida), 2000, 2nd ed.

VI. Three definitions today

The premise of this conference is that we are entering, or already in, an era of “engineering systems,” wherein the engineering profession must think holistically about large scale, complex systems. Indeed, beginning in the 1970s, engineers turned their attention to large (sometimes global-scale) systems that exhibit complex behavior. Sussman describes this era with the term CLIOS (Complex, Large, Interconnected, Open Systems) that explicitly include social, political, and economic variables in their models and definitions, and other new formulations are emerging as well.⁴⁴ Yet now field is so large, so complex itself, that we risk proliferation and confusion – if systems are everything, everywhere, then they are nothing. What, after all, could possibly unite an aircraft accident with the process for managing a large project? What is similar about a city’s atmosphere and a product design process? The three definitions of systems thinking, now hundreds of years old, help us begin to answer these questions:

Physiological systems. Some of the earliest systems thinkers were the railroad managers, faced with moving flows of goods across a broad continent. Indeed, infrastructures and large-scale systems, from manufacturing to product design, are still critical areas of systems thinking and can be understood as interlinked flows of material and information. Flows cut across different types of systems and result not from centralized direction but from the sum of local interactions. Engineers in manufacturing now explicitly think about “flow,” about a manufacturing process as a “value stream,” and about local interactions like “pull” that allow production systems to respond in real-time to customer demands.⁴⁵ In accident investigations, engineers have discovered how interactions between small, otherwise-innocuous events can lead to unpredictable behaviors, what Perrow calls “system accidents.”⁴⁶ Safety itself becomes an emergent property – if the proper rules are engineered into all the components from the start, the overall system will be robust. These components, however, are not limited to hardware but must include political and social processes like management, the motivations of designers and

⁴⁴ Joseph Sussman, *Introduction to Transportation Systems* (Boston: Artech House, 2000), 6.

⁴⁵ James Womack, Daniel Jones, and Daniel Roos, *The Machine that Changed the World: The Story of Lean Production* (New York: Harper Collins, 1990). James Womack and Daniel T. Jones, *Lean Thinking* (New York: Simon and Schuster, 1996).

⁴⁶ Charles Perrow, *Normal Accidents: Living with High Risk Technologies* (Princeton: Princeton University Press, 1999), 2nd Edition.

coworkers and legal regimes.⁴⁷ Castells identifies a “network society” that is characterized by the relationship between traditional geographic places, personal identity, and the new “space of flows.”⁴⁸

Systems of Philosophy Engineers now recognize that technology is a human endeavor, and that the line between engineering and management is often blurry. Hughes argues that the Central Artery and Tunnel in Boston began to treat the “messy complexity” of politics, social movements, and local interests not as external influences to be factored out, but as internal variables.⁴⁹ The growth of the Internet made it clear that distributed, unplanned systems could grow to be incredibly complex and powerful. Management of engineering projects is itself a complex endeavor, and may exhibit characteristics of other complex systems. Organizations can also be characterized as complex systems exhibiting behaviors like learning and stability. Our understanding of R&D has moved beyond a linear model of basic to applied research followed by development, leading scholars to speak about “innovation systems,” that include everything from education to tax policy to education infrastructure. Systems architects now recognize that politics is a real constraint on what systems are able to achieve, and may mean that the “best” solution is not always the technically optimal one.⁵⁰

Dynamic systems – Systems are increasingly non-linear and no longer exhibit clean distinctions between structure and behavior. In fact, a fixed structure leading to a determined behavior is often undesirable, as compared to a flexible system where both can change. Feedback and interactions dominate, and cause systems to evolve. Analogies to living systems are no longer to simple feedback loops but rather to complex adaptive systems. Theories of complexity are beginning to emerge that capture a variety of phenomena across different types of systems. Emergence, for example, the process whereby macro-behaviors arise out of numerous interactions of micro-behaviors, is recognized as critical phenomenon. Rather than holding to the notion “that all phenomena in the universe are reducible to the laws of physics” one should

⁴⁷ Nancy Leveson, *Safeware: System Safety and Computers* (New York: Addison Wesley, 1995), 138, 152.

⁴⁸ Manuel Castells, *The Rise of the Network Society* (London: Blackwell, 1996).

⁴⁹ Hughes, *Rescuing Prometheus*, Chapter 5.

⁵⁰ Maier, and Rechtin, *The Art of Systems Architecting*.

recognize that “all phenomena are *constrained* by the laws of physics.” Optimization is rarely possible.⁵¹ Simulations may replace predictive models as the primary tools of analysis.

An historical epistemology of “system” as developed in this paper sheds some initial light on the dizzying questions surrounding the role of systems thinking in engineering today – if only by making it clear that “system” has a long, multithreaded history. The three definitions of systems from the eighteenth century – physiological, philosophical and dynamic – help cut through some of the multiplicity and overlap, and to link today’s multiple voices on systems with their historical antecedents. We need not see the variety of today’s systems as an endless proliferation, but rather as an evolution of a rich idea, one that has always had multiple meanings and that has drawn both its limitations and its power from analogies between them.

⁵¹ Holland, John H. (1998). *Emergence: From Chaos to Order* (Reading, MA: Perseus, 1999). Also see, for examples, Joe Sussman ed., *Ideas on Complexity in Systems: Twenty Views* in this volume.

