Similarity and complementarity of science and engineering

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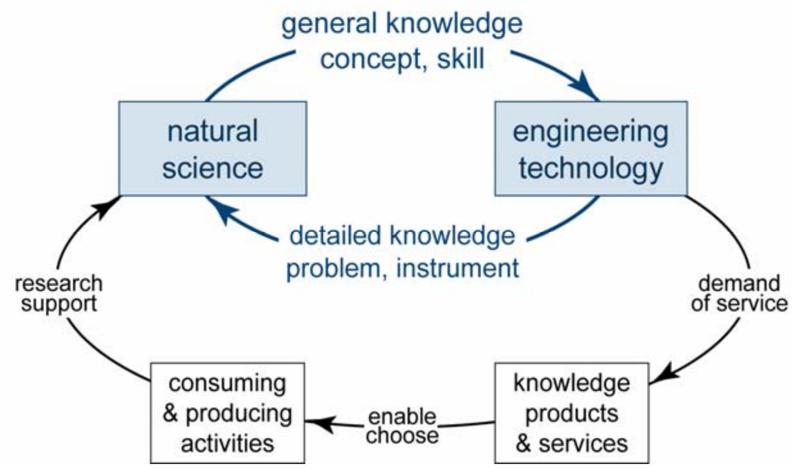
Scientists strive to understand nature, engineers to transform nature for serving people. They complement each other, for to transform nature effectively requires proper understanding, and to discover nature's secrets requires instruments to modify it in experiments. Because they both address nature, they share many knowledge and methods, although often with different emphases.



Like science, engineering engages in analysis and synthesis. But whereas scientists tend to break matter down to its most basic building blocks, engineers ultimately aim to assemble myriad components into a complex system. Because the components are heterogeneous, engineers must integrate knowledge in many areas, and multidisciplinary teamwork is common practice. Like science, engineering covers both the general and the particular. But whereas scientists tend to design particular experiments for discovering general laws of nature, engineers tend to formulate general principles for designing particular artifacts. Modern engineering has developed general theories about large types of artificial systems, notably information, control, and computation theories. These engineering theories are most effective for designing concrete artifacts, yet their abstract theorem-proof format is closer to pure mathematics than the format of physical theories, which are closer to applied mathematics. The apparent paradox accentuates the engineering emphasis on creating things rather than discovering phenomena already existent.

Unlike scientists, who can defer unsolved mysteries to future advancement of knowledge, engineers, who must deliver products on time, often have to make design decisions with incomplete knowledge. Thus engineering has developed more sophisticated ways to address uncertainties. Unlike science, engineering has explicit utilitarian missions. To reckon with utility, the contents of engineering incorporate many purposive concepts – function, performance, optimality, control, trade-off – that are absent in the contents of physical science. Unlike science, whose product is mainly knowledge, the most prominent products of engineering are things and infrastructures that permeate the fabric of modern life. Engineers are involved in the whole life cycle of technological products, from conception and design through manufacturing and maintenance to final disposal. Their jobs demand them to look beyond things to people and society. Besides designing products, they also manage workers and organize productive activities. Besides finding efficient means for given ends, they also analyze ends to find out what people require of their products.

Incommensurability versus complementarity

Talking her in Copenhagen, two of its favorite sons concerned about the human condition readily jump to mind:

Soren Kierkegaard:	*Enten-Eller* (Either/Or)
Niels Bohr.	Complementarity

Kierkegaard and Bohn both rejected the Hegelian ambition to an absolute framework that encompasses all there is to know. Yet they responded in quite different ways. I am in no position to expound these profound philosophies, but merely want to borrow some of their ideas as inspirational perspectives.

In the mid nineteenth century Kierkegaard advanced a philosophy that would be quite familiar in today's science and technology studies. Its gist is absolute disjunction, *either/or*, quite similar to Thomas Kuhn's notion of incommensurability in the philosophy of science. It is *either* technological determinism *or* sociological determinism. Technology is *either* applied science *or* social construction. Science is *either* a simple input from nature *or* devoid of reality. The paradigms are polar and incommensurate, to go from one to the other one must take a "leap of faith," to use Kierkegaard's words, or undergo a religious conversion, as Kuhn put it. This radical relativism leads to Culture Wars and Science Wars. But I will not get engaged in them.

Instead, I will adopt the perspective of Bohr's complementarity, which opts for *both* instead of *either/or*. To encompass a complementary dual for a more comprehensive worldview is not a holism in which the two sides fuse into one. To use Bohr's prime example of quantum mechanics, two representations, position and momentum, are distinctly defined. Our human condition limits us to adopt only one representation in each particular observation, but we know that we need the complementary representation for a more comprehensive understanding of the quantum world. Furthermore, it is not required that the two representations can be transformed into each other according to some prescribed absolute criteria. Uncertainty is central and intrinsic to complementarity. Under this philosophy of striving for a broad worldview in the face of uncertainty and incompleteness, I will explore technology as human knowledge.

Technological knowledge resides mostly in the disciplines of engineering and natural science. I will focus on engineering. It is most responsible for the design and production of technological goods and services, which most people identify with technology itself. Also, engineering, especially modern science-intensive engineering, is a much neglected area in science and technology studies. I will explore several complementary duals in engineering knowledge:

- Its drive for scientific foundation and its heritage as practical arts.
- The nature that engineers modify and the people that the modifications serve.
- Knowledge and uncertainty.
- Motivations of wonder and utility.
- Contents and contexts.

Social contexts of technology have attracted many scholarly works, even to the extent of crowding out science and engineering. When technical contents are discarded, "contextual" discussions of technology become *Hamlet* without the Prince of Denmark.

Complementarity of people and things

The main goal of engineering is to transform nature to serve the needs and wants of large numbers of people. This goal at once reveals its two complementary dimensions. It has a physical dimension that calls for sophisticated knowledge about nature and things, so that engineers can modify them effectively for desirable products. To find out what products are desirable, and to organize large numbers of workers to produce the goods and services efficiently, however, requires knowledge about people, and this brings in the human dimension of engineering. The two dimensions of engineering are expressed in what I briefly call physical technology and organizational technology.

The two kinds of technology can again be divided into three major kinds of activities:

- *Engineering science* for research into general principles of what can be useful.
- *Design* for developing particular products and production processes.
- *Management* for exploring ends and means, planning, and organizing workers.

The three aspects, engineering science, design, and management overlap considerably with each other. The majority of engineers engage in design. However, as a profession, design cannot work without significant input from science and management. It is through management that engineering is most tightly connected to the economy, society, and policy

The duality of engineering's physical and human dimensions confounds a stereotype. Surveying the portraits of engineers the historiography literature, B. Sinclair found: "Instead of the portrait of a profession, what we have is a grab bag of stereotypical images and they picture a group that seems politically inflexible, socially awkward, culturally limited, and ethically inert." Engineers are often stereotyped as nerds or geeks, technically proficient but socially inept, as if technical and social skills are incommensurate, so that one can only be good with *either* things *or* people. In fact one can be good with both, or neither. As a profession, engineering must be good in both to do its jobs well. Not all engineers are individually good in both, but enough number of them are to refute the stereotype. This can be seen in their success in management, both tactical and strategic.

Tactical managers organize production lines, factory floors, and supply chains. Henry Ford, an engineer, was a superb and pioneering tactical manager. Scholars have paid much attention to engineers' role in tactical management, although they often underplay the people skills involved. Moreover, they have almost totally ignored the role of engineers in strategic or corporate management.

Strategic managers design corporate architectures, steer the corporation toward long and short term goals, allocate human and other resources, coordinate production, finance, marketing, and other branches of operation. For them, adequate people skills and contextual vision are indispensable. Engineers have been outstanding as strategic managers and top executives. Ever since large corporations appeared, engineers have been successful on corporate ladders that, crowded with aggressive graduates from business and law schools, are killing grounds for the socially handicapped. From mid century to now, some 20 – 30 % of chief executive officers in large US firms have engineering background. And for each who reaches the very top, many others make senior management. The significance presence of engineers and scientists at high corporate level illustrates the importance of the practical integration of technological, economical, and other factors in competitive business operations, in other words, the complementarity of physical and organizational technologies.

Complementarity of contents and contexts

A major job in strategic management of technological enterprise is to bring together the providers and consumers of technology, to interlace technical contents and social contexts. For such jobs, and many others, familiarity with both sides gives a definite edge.

To develop a technological system require more than technical knowledge about the system's internal structures. The first and most important step in the development project is to find out the purposes of the system to be designed. What is the system intended for? What functions is it to serve? What performances are required of it? To answer them requires much knowledge about the economical, social, and environmental contexts of the intended system. Engineers must work closely with their clients and people who have a stake in it, alert them to side effects and environmental constraints, and help them to clarify their priorities and define achievable goals. The job is so important it has a special name – requirements engineering. It is often a most difficult task, especially for software, because many large software systems are novel, complex, and have endless variations. Frederick Brooks, chief engineer for developing the IBM 360 operating system, remarked:

> "The hardest single part of building a software system is deciding precisely what to build. . . . No other part of the work so cripples the resulting system if done wrong. No other part is as difficult to rectify later."

Botched requirements account for many abandoned or useless software systems. A high profile example is the air traffic control system commissioned by U.S. Federal Aviation Agency, which was abandoned after wasting more than a billion dollars. Many military and big science projects suffer heavy cost overrun because their requirements are unrealistic.

Requirements engineering aims to develop a system that works in the real world. Therefore it insists on practicality. Ideologues can talk pretty, but choices made in the real world are sometimes ugly. Many decisions ultimately rest on consumers or society at large. Yet engineers can help the clients to make rational choices under realistic constraints. They study relevant contextual factors: legal issues, safety regulations, environmental policies, cultural acceptance, and other social constraints. They explore various options available under exiting technology and scientific knowledge, and consider whether the options are achievable given the available resources. Often resource limitations force the clients to cut back on their expectations, and engineers propose trade-off for the clients to choose. Negotiations go back and forth many times, until a set of functional requirements is drafted. Then the engineers began in earnest to define the technical contents of a system whose performance can satisfy the requirements. Nothing exemplifies the complementarity of contents and contexts more than requirements engineering.

Complementarity of structures and functions

Now let us turn to the two more familiar aspects of engineering, science and design. Engineering research shifted into high gears after WWII. One result is the crystallization of several bodies of systematic and empirically tested knowledge, or several engineering sciences. Through them engineering is closely linked to the natural sciences, mostly physics, but increasingly chemistry and biology.

A natural science, such as atomic physics, takes as its topic a broad type of natural phenomena and explores *what can be* under the relevant physical laws. An engineering science is defined similarly, but instead of natural phenomena, it addresses a broad type of artificial phenomena, which is often defined by not physical properties but *functional* properties. It explores that can be *of use*.

Engineering sciences fall roughly into two groups, physical and systems. Respectively addressing structures and functions, they complement each in the design of technological systems.

1. *Physical theories*: Examples are mechanics, electromagnetism, thermodynamics, fluid dynamics, and transport phenomena, which are application to many engineering branches. They are applied physics, but not in the pejorative sense of “applied science” popular in technology studies. Engineers developed the physics laws relevant to a wide class of useful systems, introduce theoretical concepts to represent peculiarities of artificial systems, and discover general practical operating principles. They contributed much to the development of thermodynamics, fluid dynamics, aerodynamics, and other physical theories. Thermodynamics originated in studying the performance of steam engines and other heat-utilizing devices. Its practical heritage

is apparent in physics textbooks, which discuss heat pumps and the Carnot cycle – Carnot was an engineer. One formulation of the second law of thermodynamics itself is the impossibility of perpetual motion machines.

2. *Systems theories*: Examples are control theory, information theory, computation theory, theories for estimation and signal processing. Most systems theories are indigenous to engineering. In contrast to physical theories, they abstract from *physical* properties and focus on the *functional* properties of systems. A thing's function is its behavior that impacts on a larger context or the service it renders an external community. Function is a purposive concept that seldom appears in the physical science. It is central to engineering because the purpose of an engineered system is to provide services. Engineers are responsible to design the structure of the system so that it performs those services satisfactorily. Complementarity of internal structures and external functions are crucial to them.

Consider for example trains powered by steam engines. For a train to travel with a steady speed, its engine must work harder when it climbs an incline than when it travels on leveled ground. To achieve this James Watt invented the flyball governor to regulate the operation of the steam engine. The physical *structure* of the governor utilizes the centrifugal force of a pair of fly balls to move the valve that controls steam input into the engine. However, engineers also abstract from these specific physical characteristics to examine the governor's general *function* of controlling the engine so that its load – the train – operates at a steady pace. This functional analysis is the job of control theory. Control theorists discover the principle of feedback control underlying the flyball governor, a principle applicable to maintaining steady operations for a wide variety of physical systems. General knowledge about feedback control enables engineers to invent new controllers with other physical structures that are effective in other physical situations, for instance the electronic cruise control that keeps your car moving steadily at 100 kilometers per hour on an undulating road.

Complementarity of the general and the particular

Theories in both engineering and natural sciences usually offer general principles and frameworks, often mathematical and rather abstract. On the other hand, an engineering design or a scientific experiment is always a particular undertaking, replete with its peculiar concrete details. Relations between theory and experiment, or between science and design, are also the relations between the general and the particular.

General principles sacrifice details for covering large scopes. Particular descriptions sacrifice scope for accounting details. How to connect the general and the particular is always a difficult problem. A manifestation of this difficulty is the tension between the philosophy and sociology of science and technology. Unable to connect the general and the particular, scholars opt for *either* macro philosophizing *or* micro sociological portraits. Their bitter debates sound as if the two views are incommensurate. In contrast, the success of natural sciences and engineering lies in the complementarity of the general and the particular.

The power of a science can be measured by how rigorously it ties together general principles and particular instances. The physical sciences and engineering are powerful in this sense. The connection usually involve several steps, each step narrows the scope by specifying more details. For example, Newton's laws of motion provide general principles of all motion. They leaves out the form of the motion-generating force, for example the gravitational force, the inverse square law of which Newton introduced separately from the laws of motion. The force can be electromagnetic, which will lead to a separate range of phenomena. Within gravity, a narrow scope focuses on the solar system, and a particular instance of the solar system was the return in 1705 of the comet previously known as the Spirit of Caesar or the Wrath of God. Similar hierarchies of generality are found in engineering science. For instance, Claude Shannon's information theory lays out the general bounds for reliable communication. A systems theory that focuses on communicative functions, it leaves out the physical media of communication, which can use copper wires, optical fibers, or wireless, propagation in free space. A narrower scope is the study of optical communication through glass fibers. A still narrow scope is the OC1 system of optical communication, which can carry 672 simultaneous telephone conversations in a single strand of glass fiber the width of a human hair. An instance of it was the first system rolled out in Chicago in 1977. The intermediate steps are important, because they ensure that the justifications for generalization can be clearly stated and criticized.

The ability to proceed from general principles to particular instances underlies the ability to predict and explain. This is not easy. For instance, Charles Darwin introduced broad principles on evolution: descent by modification and natural selection. They are powerful but not powerful enough to predict or even explain satisfactorily the emergence of specific species. Predictions require not only deduction from principles; they require additional input about specific conditions relevant to the instance at issue. Knowledge about appropriate conditions is usually complicated and requires much research to ascertain.

Galileo gave a simple example. He distinguished between "machine in the abstract" and "machine in the concrete." The principle of lever, a basic principle for constructions, had been known since Archimedes. This, Galileo said, was only machine in the abstract. Archimedes could boast that he could raise the earth given a pivot only because he had ignored the kind of lever required for the job – any realistic level would break. For machines in the concrete, the abstract lever principle must be supplemented by conditions such as the lever's strength and bending under load, which would vary according to its particular material and structure. To acquire systematic knowledge about these conditions took almost two centuries before engineers confidently build long bridges and tall buildings that bear heavy loads.

Complementarity of analysis and synthesis

The debate between holism and reductionism is a familiar topic in science and technology studies. In the extreme positions, radical reductionists insist that a whole is *nothing but* its parts, if you know the parts, then you know all there is to know. Radical holists insist that a whole is a whole that is destroyed by any attempt at analysis. The anti-analysis position is captured in the "seamless web" metaphor; a seamless web allows no parts, because it unravels at the tiniest loose ends. “Seamless web” and “nothing but parts” are incommensurate; you must stay at *either* the top *or* the bottom.

A far more productive approach is to regard the whole and the parts as complementary and investigate the connections between them. Socrates adopted the method of division and collection, Galileo, of resolution and composition. Descartes and Newton talked about analysis and synthesis. Engineers practice functional decomposition and physical integration in systems design.

A long list of scientific successes, from subatomic physics to molecular biology, testifies to the power of analysis, in which scientists seek the basic constituents of complex systems. This is partly because the properties and interactions of the basic constituents often turn out to be the fundamental principles underlying the properties of larger systems that they make up. Nevertheless, radical reductionists who jump to the conclusion that large system are nothing but their constituents have overlook the equally prevalent phenomenon that scientists seldom if ever stop at the constituents. As soon as they figure out the behaviors and interactions of the constituents, they turn around to investigate how the constituents make up infinite variety of compounds. They turn from analysis to synthesis, which is often a turn from general principles to particular instantiations of the principles. Thus atomic physics explores the structures of atoms as wholes composed of nuclei and electrons. More recently, as soon as molecular biologists decipher the detail structures of genes, they turn to genomics for answers about how genes and their interactions contribute to the physiology of organisms. Analysis is not reductionism. It decomposes a whole into parts, but does not assert that the parts are all. Scientists realize that to understand anything of complexity, one must pull it apart, study its details in depth, and then put it together again. Thus synthesis complements analysis.

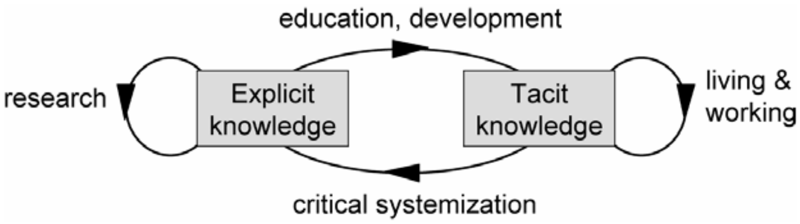
The major aim of engineering is to design and build particular systems, which are wholes comprising many parts. Engineers depend on analysis-synthesis as much as scientists, but perhaps with different emphases. Just as scientists tend to emphasize general principles and engineers particular designs, the former lean toward analysis and the latter synthesis.

Natural scientists often analyze existing phenomena replete with concrete details. Engineers differ from natural scientists in that they primarily aim not to understand existing phenomena but to create systems that do not yet exist. Therefore they start with an abstract conception of the whole system, for example, the idea of a fuel-efficient airplane. The conception is centered on a set of functional requirements: what the intended airplane is supposed to do, what service it is to perform. Then they analyze the conceptual airplane into subsystems, often along *functional* instead of physical lines, for instance, the subsystems of the airplane *for* propulsion, lift, and payload, which are to be physically realized as the engine, wing, fuselage. In the functional decomposition, it is most important to specify how the subsystems will work together, what life and propulsion would support the required payload. When engineers have a reasonable conception of a subsystem, for example a jet engine, they then decompose it further into smaller subsystems, until they arrive at parts simple enough to be specified to the last detail. These small parts are then manufactured according to specification, tested, assembled into subsystems, and so on, until finally an airplane is ready for test flight. This round trip from the whole to the parts and back, from the top to the bottom and back, consists many smaller round trips of analysis, design, synthesis, testing, feedback. Analysis and synthesis complement each other on many levels.

Complementarity of science and art

Art and science are sometimes regarded as incommensurate paradigms. However, the two are not diametrically opposite, neither are they mutually exclusive. Being scientific implies being rational, critical, and systematic. In this sense, art, in contradistinction to arbitrariness or mechanical routine, is scientific to some degree. Aristotle remarked that *téchnē* (art) has its intrinsic *logos* (reasoning), and it is the possession of true reasoning that distinguishes art from mere experience or blind cut-and-try. Perhaps at Aristotle's time and long after, the reasoning in the state of art fell short of the clarity, criticality, and systematicity of modern science. Practical arts in construction and machinery contained many principles, rules of thumb, and facets of scientific knowledge. But these were either too weak or too limited to deal with the complexity of real world conditions, so that practitioners relied mainly on intuition and trial and error. Nevertheless, over the past century they have so advanced their reasoning that modern engineering is largely scientific.

Science generally means possessing knowledge that is sufficiently general, clearly conceptualized, carefully reasoned, systematically organized, critically examined, and empirically tested. However, because scientific knowledge is limited by human understanding, which is finite, it has no claim to exhaustiveness and absolute certainty. Much remains unknown in science and engineering. Much knowledge remains intuitive; in other words, much remains an art. Modern engineering has developed many engineering sciences, but it has not outgrown its practical arts root. It never will, for art and intuition knowledge is continuously being generated in life and work.



Scientific knowledge is mostly explicitly articulated and clearly represented. However, much knowledge in engineering and technology is not explicit but tacit, not written out but embodied in:

- human capital: human skills, experiences, understanding, practices
- social capital: work organizations and institutional structures
- physical capital: plans and operations of machines and plants.

Explicit knowledge can be quickly disseminated because it is clearly explained and easily taught. Implicit knowledge cannot. Experience cannot be taught; it can only be patiently acquired through practice and accumulated over time. Tacit knowledge is the most valuable asset of technologically advanced nations, their greatest comparative advantage over catcher-ups. The transmission of tacit knowledge in "technology transfer" depends heavily on the travel or migration of technical experts and managers, and the moving or building of physical plants.

Explicit knowledge can be subject to rigorous arguments and tests. Tacit knowledge is much less susceptible to critical examination, and hence to improvement. There is a continuous effort to make tacit technological knowledge explicit, to make art more scientific. It runs simultaneously with efforts to produce more sources of tacit knowledge through education and social and industrial development. The cycle drives the technological progress.

Take for example the technologies of large-scale manufacturing of cars. As is well known, mass manufacturing, which capitalized on the economy of scale, was the leading technology that made Detroit the car capital of the world. Then beginning in the 1960s, the Japanese, especially Toyota Motors, developed a better technology, which the Americans call "lean production." In mass production, assembly lines and their parts suppliers pump out as many pieces as fast as possible. In contrast, the "just-in-time" supply chain of lean producers strives to produce just the right things at the right time. In mass production, assembly lines spit out cars of various qualities and leave it to quality controllers to weed out the defective ones. In contrast, the "total quality control" of lean producers stops the assembly line any time a worker spots a defect, so that defects are nipped at the tip. Total quality control and just-in-time production are difficult technologies, because they involve not only one factory but the entire automobile industry with thousands of suppliers in many nations. Toyota took decades to develop it. It was so successful that in the 1980s Americans were panicky about being overwhelmed by the Japanese. Industry and academia teamed up to respond to the challenge; MIT, for instance, initiated a big program. Engineers have ferreted out many principles underlying lean production practices. Books are written and seminars held. Thus tacit knowledge originated in industrial practice is made partially explicit. However, much of it remains tacit and embedded. Tried as they did to copy lean production practices, American manufacturers have so far fallen behind Toyota in efficiency. The science of lean production is shared, but the Japanese are superior in the art. Even so, decades of competition advanced the technology of automobile manufacturing in both countries.

Complementarity of knowledge and uncertainty

Explicit and tacit, our knowledge of the world is far from complete. As Einstein remarked, certainty is unattainable in natural science, not to mention in daily life. However, postmodernists are wrong to jump from the lack of absolutely certain knowledge to the dogma that science is nothing but politics, in which anything goes.

Scientists and engineers are doers, not empty talkers; bold, but not reckless. They are aware of desirable ideals, but they are also realistic about what they can achieve. It is well to be able to know everything all at once, exactly, and with certitude. But that goal is unrealistic. The success of science and technology depends partly on the patience to take one step at a time and bite off what one can chew. One common practice is to idealize closed system in an open universe, as in controlled experiments and limited models. Scientists and engineers make approximations and acknowledge the approximations by estimating errors and introducing corrective steps whenever possible.

Engineers design products that will be used by real people in the real world. Safety and reliability are paramount. When engineers are uncertain, they prefer to err on the safe side and use tried methods. Bold designs may be exciting and glamorous, but their risks of failure are also greater, and at stake are lives and properties. “When in doubt, be stout” is a dictum I heard in the first lecture of two separate freshman engineering courses. For this engineers are often stereotyped as conservative, dull, and unimaginative. The stereotype is unfair. Engineers are conservative, but not from lack of imagination but from their sense of responsibility.

At the frontier of research, scientists always face the unknown. When they are unable to solve a problem, they leave it to future research. Newton did not like the idea of gravity acting at a distance. He calmly said that he did not know the cause of gravity and left it to future generations. Three centuries passed before Einstein filled the gap in Newton’s knowledge.

Waiting is a luxury engineers can ill afford; they have to deliver products in time. The practicality of their mission is a heavy burden that forces them to make decisions and take actions, even in the face of incomplete knowledge and uncertainty. Here is where critical rationality, the sense of responsibility, and the effort to seek alternatives become most important. Hard choices under practical constraints are often unpleasant and ugly. Ideologues demand perfection and absolute safety; they can talk pretty because they do not bear responsibility for their grandiloquent. Engineers ask “How safe is safe? How much are you willing to pay for additional safety?” Ideologues denounce engineering trade-offs as crass and vulgar, but what practical alternatives have they offered? To avoid hard choices is a choice, an easy but often most irresponsible one.

Science and technology have brought an enormous amount of knowledge, explicit and tacit. They have also shown how much we do not know. This complementarity is captured in Confucius’ remark: “To know what one knows, to acknowledge what one doesn’t know, that’s knowledge.”

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