Chapter 7

Engineering Design and Society

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As a discipline, engineering has remained rooted in mathematics and natural sciences throughout recorded history; as a practice, it is social at its core. A large part of engineering is, and always has been, a craft based on imagination and ingenuity combined with day-to-day incremental learning from practical, shared, inherited, and emulated social experience. Motivation for most engineering is to improve our individual and collective lives, but its consequences can extend far beyond the intent.

For example, fences surrounding early human dwellings protected them from marauding animals and people; these very fences shaped our civilization and society through many consequences not anticipated at the outset. In exploring the linkages between engineering and society, it is useful to keep in mind both intended uses and unintended consequences that arise or are discovered later through complex social interactions. Only a part of engineering's ultimate impact on society can be deliberately targeted, or even imagined, at the outset.

Objects of natural science and products of engineering are not sentient. Absent self-consciousness, such objects are not aware of any laws or regularities that we may discover about them, or of human purpose behind the artifacts or processes that may be designed by engineers. This ignorance lends robustness to knowledge in the natural sciences and the properties of engineered products.

Social science is a more recent development than the society that it seeks to document and understand—perhaps as recent as Aristotle (4th century BCE), Kautilya (4th century BCE), or Ibn Khaldoun (14th century AD). As a discipline,

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social science faces a more difficult challenge. Since societies comprise self-conscious human beings endowed with at least a degree of free will, the explanatory power of any laws or regularities in social science tends to be lower. Moreover, self-conscious humans are prone to alter their behavior in response to any regularity social science may discover and reduce the robustness of such laws to their own discovery.

Bringing social science into engineering design has its pros and cons. Identifying diverse interests in engineering design is only the first step. Legitimate interests must be separated from interests that are best ignored and set aside. The remaining interests have to be assigned some reasonable weight in a space of incommensurate interests. Will engineering design still be possible when all legitimate interests are given reasonable weight? Will the results satisfy everyone, or be acceptable to all? New York did not extend its subway system to JFK airport, but built a separate line, presumably to accommodate the interests of taxi and limousine companies and drivers. Is that a better solution for society? Might it have been better instead to design the best “engineering” solution for transportation to JFK airport and deal with the political fall out afterward?

Differences in, and mutual engagements of, engineering and social science are interesting and important. Engineers design ways and artifacts to do things better; social scientists concern themselves with understanding how things are, and why. Engineering measures itself by its ability to change lives; intervention is less welcome in social science. Unlike social science, engineering is concerned with objects. Absent consciousness in its objects, the principles of engineering design are robust to variations in time and space; social science has more difficulty identifying regularities that are robust even to their own discovery. The successes of engineering are easily seen in society’s high regard for them, but social engineering evokes skepticism and suspicion.

These disciplinary differences are rooted in the strategic use of information by conscious (not material) objects of study. However, in practice, engineering and society interact intensively and shape each other. Through its myriad innovations—fire, weapons, tools, and processing—engineering has radically redefined the very nature of human society since prehistory and it continues to do so. In this way, modern society is an offspring of engineering, while much of engineering is also an outcome of social organization, human relations, and interactions. Engineering is a deliberate, purposive activity of individuals or groups seeking their objectives. Social phenomenon, on the other hand, is conceptualized at an aggregated level as a consequence of individual behavior. Engineering is a practice; society is the result of many such practices.

This paper explores the mutual relationship between engineering and society and the ways in which social science influences the effectiveness of engineering design and interventions. This examination of design and social science is organized into six sections centered on information.

1. **Information and Design:** *Science creates information; engineering encapsulates the information discovered or extracted by science into the design of artifacts to suit our wants, and thus it redefines work, lives, and ultimately society.*

Scientific knowledge (natural as well as social) expands our information set about the world. When we use this information to effect change—often in an attempt to improve our work and life—we practice engineering. Society (an interactive network of individuals) and engineering are in this sense inseparable. It is useful to explore the nature of this linkage by probing into the nature of work.

Work involves an entwined matrix of physical action and information processing. The consequences of rearranging action with the use of knowledge pervade society. The act of writing, for example, consists of obtaining a piece of paper, finding a writing instrument, and moving one's hand (all actions) guided by information about the location of the writing materials, what words or figures to draw, and how to draw them. Technology can change these relationships; consider the example of the shift from handwriting to typewriting in the 19th century. The introduction of the typewriter replaced the need for knowledge about how to form letters and words using a pen or pencil with the knowledge about how to make and operate a typewriter. Typing technology retains paper, but replaces a pencil with a ribbon and the knowledge of letter formation with preformed typefaces. This technological invention comprises a much larger body of knowledge including conceptualization, design, manufacture, and distribution.

Learning to write in grade school can now be confined to character recognition and exclude character formation.¹ Legible writing is speeded up and is read faster to save time at both ends. Writing is standard in form and character spacing. New classes for learning typewriting in schools and businesses appear and the “typist” appears as a new business professional. The potential for errors creates a demand for specialized proofreaders and symbols for copyediting. New industries for making and repairing typewriters and keeping them supplied with ink, ribbons, and replacement parts are born. This generates a demand for labor, materials, manufacturing machines, space, financial capital, power, and entrepreneurs. Supply lines of production are adjusted to fit the new technology. Today, typewriters have been replaced by computers and printers whose origins and consequences have little continuity with the technology of “writing” they replaced. Engineering innovations ripple through all aspects of society.

Many other examples of how engineering innovations shape our work and all aspects of society exist: the replacement of horse carts by trains and automobiles radically altered not only transportation but also the design of cities and towns; it led to the creation of roads and rails, new sources of energy, businesses, social interactions, manufacturing, retailing, skills, professions, colleges, educational

¹The average quality of handwriting is said to have deteriorated during the recent decades, just as the introduction of calculators is said to have trimmed the ability to calculate. Whether elementary schools should allow/encourage mechanical aids for writing and calculation remains controversial.

programs and diplomas, and academic disciplines. Not every engineering consequence is positive however, new technologies also give rise to new methods of waging war, killing, exploitation, and poverty.

Design gives body to information about the laws of nature in the material world and to our wants in the social world. The ancient human desire to fly like a bird only ended in broken bones or tragedy, until the Wright Brothers brought their perspective of the laws of nature to build their flying machine. A century later, every component of a jet aircraft encapsulates vast amounts of information to realize that dream for the masses.

Civilizations accumulate information and the consequent capacity to design and build both physical and institutional artifacts. Revolutions transform or destroy the accumulated artifacts in order to begin anew with a clean slate.

Artifacts alter existing designs (well beyond their makers' intent) in stages or layers. When a design is sufficient and successfully executed, for example, a bicycle, the first layer defines the intended change—easier and faster travel on the new machine. Increased demand for use adds subsequent layers—the straightening and paving of cow paths, the design of houses, the layout and density of towns, training people to build and maintain the bicycles, places to park, store, and secure the new machine, demand for bicycle parts, and movement of materials and people to support the technology and economics of the new artifact. Every layer calls for new information, possibly discarding some information, skills, facilities, parts, and organization previously needed for the displaced artifacts (e.g., saddles, food, shelter, and care for horses).

The consequences of engineering pervade all aspects of our work, redefining information and skills needed for a given function thus generating new kinds of work, while making others obsolete. It also redefines how we live, spend our time and material resources, relate to one another, and what is produced, where, and by whom. It redefines who consumes it and consequently trade and commerce, the distribution of wealth, and the social and political architecture that supports us. However, most if not all of these social consequences of technology are unknown and possibly unknowable to the inventor of the artifact at the time of its design and introduction. Henry Bessemer could not have predicted the global consequences of the large-scale production of iron from the blast furnace he designed to smelt iron ore; his purpose was local, but the consequences of his design were far-reaching in time and space. In economics, the distinction between partial and general equilibrium recognizes this layering of consequences.

2. Replication and Scale: *The replication of material is expensive in effort and time; the replication of information is free.*

Transforming lumber into ten chairs of a given design takes a carpenter almost ten times as long as it takes to make one chair; however, the design of the chair (and the information encapsulated in its design) can be replicated endlessly without significant additional effort. In other words, the cost of production in transforming materials is variable, but the cost of information embedded in the design is mostly

fixed (with respect to the number of units to which it is applied). By incorporating more information into product design, the (hardware or software) engineer substitutes variable cost by fixed cost. Increasing the fixed costs does not make sense unless we consider the economies of scale. No matter how large the additional fixed cost, increasing the number of units always reduces the cost per unit. When the number of units demanded and produced is raised sufficiently, the unit cost falls below the original variable cost.

Falling unit costs arising from engineering design, which appear to be a blessing at first, have extensive economic and social consequences. Not all of these consequences increase social welfare. The least-cost mode of production is a monopoly, but the monopolist may exploit market power to sell fewer units of the product at a higher price to maximize profit (in comparison to competitive equilibrium levels of price and quantity). An economy dominated by a monopoly also has less product diversity and fewer opportunities to learn and innovate.

Unless they are carefully controlled, a monopoly's consequences in the form of stifled innovation, high prices, and product rationing are norms, not exceptions, and arise from embedding information to improve the design. Indeed, most major technology firms in recent decades, including Westinghouse, General Electric, IBM, AT&T, Microsoft, and Google (renamed Alphabet), have been restrained by antitrust authorities in the US and the EU. Database technology introduced massive economies of scale in accounting and other operating costs of financial services in banks, insurance, and mutual funds. The cost of developing software to maintain a thousand customer accounts is not much lower than the cost of software for hundreds of thousands of accounts. These economies enabled the consolidation of financial service firms and the growth of behemoths such as J.P. Morgan Chase which are not only too big to be allowed to fail but also too big to jail in democratic polities where donations finance political election campaigns. It has been argued that the Atlantic Financial Crisis of 2007–11 may have been rooted, at least in part, in information economies of software design to operate financial service firms (Chaudhri et al. 2018).

3. Choice Criteria: *Engineering, economic, social, and moral interpretations of efficiency form a hierarchy, and their precision and completeness decline with the increase in relevance to society.*

Efficiency, over the spectrum of its varied forms, is the criterion for making decisions and evaluating outcomes. In engineering, the efficiency of an artifact is defined as the ratio of its output to input, each measured by a single variable, e.g., a vehicle's miles per gallon of gasoline or the percent of the metal content extracted from ore.

In the presence of multiple inputs and/or outputs, it is useful to convert each of them into a common unit before calculating the efficiency of the artifact as the output/input ratio. For example, if the inputs consist of multiple types of fuels, they might be converted into equivalent British Thermal Units (BTUs) to calculate efficiency. When such equivalence across incommensurable inputs or outputs is not

meaningful, it is useful to switch to economic efficiency by converting various inputs and/or outputs into units of money before calculating efficiency. The cost in dollars per gallon of gasoline dispensed at the gas station is calculated from the cost of many inputs for producing, transporting, storing, and delivering the fuel to car tanks. Some economic measures of efficiency leave out variables which cannot be converted into money (human life, morality, beauty, etc.).

Both engineering and economic measures of efficiency are computed from a single point of view—the party who contributes the inputs and receives the outputs of the process. In social settings, two or more points of view are present, and each party views the process on the basis of efficiency of resource costs and benefits accruing to that party. The same process can be attractive for some, but harmful to others. A Pareto efficient process is one that benefits at least one party without hurting any of the others. Unlike engineering and economic concepts of efficiency, the Pareto criterion is incomplete because generally it cannot rank all of the processes in order of their attractiveness; it is possible for some processes to be neither more nor less Pareto efficient when they confer advantages and disadvantages on different parties.

Moral criteria lie on the spectrum of efficiency concepts beyond engineering, economic, and Pareto considerations. The interests of some parties may be excluded on the grounds of being morally inadmissible. In a society with property rights, better locks may be morally efficient even though they may deprive thieves of their livelihood. The identity of parties' whose interests are admitted to efficiency calculation is a moral, not technical, judgment. Moral criteria may also include the cross-sectional distribution of the consequences of an engineering choice borne by various members of society. For example, fairness may lean in favor of equality or toward the weaker sections of society.

This hierarchy of engineering, economic, Pareto, and moral efficiency takes us from uniqueness, clarity, hardness, and completeness at one end toward multiplicity, ambiguity, judgment, and incompleteness at the other. Arguably, it also takes us in the direction of greater relevance to society and creates a difficult-to-resolve tension for engineering design. Which criterion or criteria can one use to identify which engineering designs are better for society? Can we determine the chosen efficiency of the proposed designs *ex ante*, especially in the presence of risk and uncertainty, and the differential spread of costs and benefits over time? If so, how?

4. **People:** *As self-aware, thinking, and sentient beings, we respond to all-natural and engineered changes in our environment; our faculties to learn, conjecture, and anticipate lead to the indeterminacy of, and difficulty in predicting outcomes in social systems.*

In predicting the social outcomes of engineering interventions, we face major hurdles. First, unlike inanimate objects, human beings remember, conjecture, anticipate, learn, strategize, and react to changes in their environment. Each act of engineering alters the environment and induces changes in the behavior of people in that environment. These changes can be direct (e.g., one's commuting route after construction of a new bridge) or indirect (e.g., living farther from the place of work

after construction of a faster highway or commuter railway line). Engineering-induced indirect changes permeate society. Yet, it is difficult for the engineering designer to anticipate even a significant proportion of these consequences of design in a complex system.

Second, humans deliberately create new ideas and things that did not exist or had not been imagined before. In choosing a courses of action, we exercise free will, making it difficult to predict what an individual will do on the basis of past observations. Choice theory seeks to explain human behavior by postulating unobservable preferences, which in turn are estimated from observed past behavior. Absent a modicum of stability and generalizability in time and space (which would allow one to postulate that the data on behavior at one time or in one situation can be used to estimate preferences applicable to behavior in another time or place), choice theory risks becoming circular, and therefore moot in furnishing useful explanations or predictions of individual behavior.

5. **Dispersed Information:** *The outcomes of extended order cannot be predicted with the limited access to the microlevel knowledge in possession of individuals (Hayek: The Fatal Conceit).*

A third hurdle facing engineers in trying to predict the social consequences of design intervention arises from the dispersed nature of information in society. A large part of information comes to individuals as a by-product of living daily lives observing and doing things. Gathering all this information at a central location to make it available to a decision-maker is difficult, if not impossible. Asking individuals to share such information raises the possibility of strategic manipulation, withholding, and refusal to reveal the truth. Hayek (1991) points out this fundamental and pervasive handicap of central planners. It also applies to engineers trying to design an artifact for a targeted social consequence. Determining where and what kind of highway or bridge is built, and how much tax money is spent on elementary education or public health, are examples of this difficulty. Nelson (1977) points to the shortcomings of the economic, organizational, and scientific approaches in helping make normative judgments on public policy. The metaphor in the title of his book refers to the relative ease of putting man on the moon as compared to the difficulty of improving the education of children raised in poverty.

6. **Evolution:** *Engineering designs are mutations; some disappear in the emergent process of social evolution; others are adapted and lose their identity; some survive in a secure niche to furnish ambient variation, while a few spread widely to redefine society.*

From the point of view of social consequences, engineering design can be seen as a biological mutation in genes in our macro domain. To the best of our knowledge, biological mutations are random errors due to copying or exposure to radiation, and follow no known pattern. In design, the creative spark and imagination is the “random” stimulus. Most changes in design may have no detectable consequences. Some mutations diminish the fitness of the organism in its environment and tend not

to survive over time. Others may survive but are adapted over time through subsequent mutations to the point where they lose their distinct identity. Many surviving mutations, like Darwin's finches on the Galapagos, find and survive in their own narrow niches. Radical innovation does not occur in biology—the gills of a fish are not replaced by lungs in its offspring in a single mutation.

Hyperbole aside, almost all engineering designs are evolutionary, not revolutionary. Like DNA, the design also encodes information from past experience and newer insights and hands it to the next generation. This chain of encoding an increasing amount of information in surviving design is a function of social, political, and economic organization and stability. The lost engineering of fallen civilizations and the puzzlement during the dark ages that follow are the norms, not exceptions; the metallurgy of the massive iron pillar of Delhi, which remains rust-free after 15 centuries, had been lost to mankind until the early twentieth century.

Concluding Remarks

The distance between various disciplines and their corresponding practices varies. This distance is narrower in engineering, but relatively large between social science on the one hand and society on the other hand. The practice and discipline of engineering interact more intensively and contribute more to each other. Obviously, society shapes social science, but the influence of social science on society is weaker to the extent that, in some quarters of social science, interest in society itself starts and ends with being the object of their scholarship and source of observations. The practice of engineering is purposive while society is an aggregate-level phenomenon to which purpose is not easily ascribed. Engineering design often serves as an intervention and alters social relationships that social scientists study. The adoption of an engineered product becomes part of the social fabric and an object of study in social science. Known properties of this changing social reality are not as robust as the objects of engineering.

Items (4) and (5) in the list above illustrate the difficulty of predicting the social consequences of engineering designs or designing an intervention to achieve a given social consequence. Their social level consequences, especially in the second and higher layers, become known only with experience after the design is implemented. These social consequences emerge from myriad interactions of sentient individuals with the design, and with one another. The complexity of these individual interactions can be analyzed statistically or simulated if we have access to sufficient knowledge of rules of their dynamics; however, the latter is rarely possible.

Whether or not social science can serve to inform better engineering design depends on our ability to understand and predict the social consequences of design. The social effects of engineering design may vary by context and a design targeted for one context may not have its intended effect in another. Beyond traditional engineering, products such as robots with limited self-consciousness and social ability may change the meaning of social relationships. When products have the potential to be autonomous agents, social science will face new challenges.

Fortunately, all is not lost. Gode and Sunder (1993) report evidence that it is possible for markets to have certain well-defined and predictable properties even if the behavior of individual agents is unpredictable. Identifying corresponding propositions about interaction between the design and society may be a fruitful line of inquiry. Until we learn more, we have to be modest about the ability of social scientists to help design better physical or institutional artifacts on the basis of *their science*—the documented laws of their discipline.

Social scientists can conduct surveys before the designs are implemented or study the reactions and consequences afterward by gathering and analyzing data. But it would be unwise to expect much predictive power from social science about the effect of these designs on society. With rare exceptions—e.g., Ibn Khaldoun (1958 [1377])—the record so far does not support much confidence, especially in establishing causality and out-of-sample predictive power. Engineering has not done too badly being on its own. The grass in the social science yard may seem greener than it is from the engineering side of the fence.

Consequently, one may argue that social science is robust only to a certain extent as it tends to study how things are when technology and social context change. So it may be that we are chasing a chimera of science in social science rather than seeing its role as one of studying how things are in a socio-temporal context while looking for “some invariants” that could help us predict the change that an engineered product may have. In some ways, it is like regulating a new technology; regulation lags the introduction of technology because it is difficult to predict any consequent social failures, especially emergent unanticipated interactions. However, social science may help us know the types of social failures that we may have encountered before in the introduction of prior technologies. For example, one could argue that the Wright Brothers’ airplane is not the same as a Boeing jet in spite of them sharing the physics of aerodynamics. They do not share the physics of a jet engine which was developed in a different society and technological environment many decades later.

We can ask people potentially affected by design to contribute suggestions and an alternative design. Field or beta tests and focus group assessments of new products and services are a common practice. This can yield unanticipated glitches and new ideas for the designer. It also renders radical innovation less likely to succeed if it does, or appears to, hurt the interests of some well-organized interest group. The nonexpert users can add a valuable perspective, but they also lack the big perspective that a Steve Jobs for example may bring to redefining the cell phone instrument. Holbrook (2016) suggests that new airports around the world seem to be made for everyone—cities, airlines, retailers, architects—but passengers. Given the opportunity to alter a design, will people at large help improve engineering? We do not yet know the answer.

Alternatively, we can take a narrower engineering efficiency perspective at the design and construction stage and let the acceptance of design to society be sorted out after the fact in a manner parallel to how nature accepts and rejects biological mutations. Of course, the rate of rejection of biological mutations is high and may be lower in engineering design. Experience with a given design will yield feedback

to the designers, who may include it in the next generation of designs; however, this manner of using feedback is slow and can be costly in the long run.

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