

1

Compromised Exactness and the Rationality of Engineering

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1.1 Introduction

In the spring of 1929, on the occasion of the Gifford Lectures at Edinburgh University, John Dewey asked: ‘Are there in existence the ideas and the knowledge that permit experimental method to be effectively used in social interests and affairs?’ (Dewey, 1988, p. 218). By ‘experimental method’, Dewey meant systematic reasoning about effective means for achieving a specified end. This was problem-solving reasoning *par excellence* for Dewey, because it was reasoning that was reflexively shaped by its consequences in a cognitive positive feedback loop characteristic of applied science and engineering. It was just this ‘experimental method’, Dewey argued, that by uniting the results of experiment-validated scientific knowledge with the objectives of engineering practice had enabled the society- and culture-transforming accomplishments of nineteenth-century technological innovations. What Dewey was asking in the Gifford Lectures, then, was: Do we know enough, not *in* science and engineering, but *about* the methodologies employed in applied science and engineering, to apply those methodologies to ‘social interests and affairs’?

Here we are, eighty-six years later, asking the same question: Is there, in the kind of reasoning routinely employed so successfully by engineers to solve technical problems, a model for the design of more effective social systems? Do we, today, know enough about engineering practice – specifically engineering practice rather than the practice of science – to help us formulate more effective public policies, create more effective organizational structures and develop better social systems: educational systems, health-care systems, judicial systems, financial systems, even political systems?

A first step towards answering these questions would be clarifying the distinctiveness of engineering reasoning *vis-à-vis* scientific reasoning. This would help us to understand why it

is that we ask about a model for developing better public policies and better social systems in engineering and not in science.

A second step would be to describe the centrality to engineering reasoning of the design process, and within that process, of trade-off decision-making, in order to assess its transposability to the design of public policies and social systems. Even if it seems transposable in principle, however, the roles of two fundamental features of engineering practice in the reasoning underlying the design process must be taken into account, namely, its experimental and its evolutionary character.

Of course, people have been designing and redesigning social systems, and implementing public policies, for all of recorded history, and for a long time before that. As nearly as we can tell, they did this without asking for help from the ‘engineers’ of the day, that is, from contemporary possessors of craft know-how. What seems new in assessing social systems today is a perception on the one hand of manifest expertise in applied science and engineering and on the other hand of a problematic situation confronting humanity for which science and engineering clearly bear some responsibility: a technology-enabled, globalized social, political and economic life causing a threatening reaction of the physical world to our science- and technology-based action upon it. The distinctive re-engineering of human being in the world that has taken place over the past 200 years has clearly contributed to this threatening situation, so, we ask, can engineering show us how to ameliorate, if not resolve, its most threatening features?

That question will be explored here, beginning with putting the perception that science and engineering could play a role in designing new social systems into a historical context. As a matter of fact, this perception *has* a history, one extending back some 400 years. That it does, implies that the turn to science and/or engineering today for guidance in formulating public policies and designing social systems is not uniquely a response to today’s technology-caused problematic world situation. Long before that situation arose, people had proposed basing social systems on science or engineering. Exposing the history of such proposals may thus shed light on the motives, and prospects, for turning for help now to engineering practice.

1.2 The Historical Context

Claude-Henri de Saint-Simon and Auguste Comte were perhaps the first people to propose a wholesale reorganization of society – in truth a re-engineering of society – in order to put scientists and engineers in leadership roles, alongside industrialists and financiers. New forms of science-informed, technology-driven industrialization were then just beginning to be recognized as constituting an ‘industrial revolution’ that was creating a new basis for prosperity for society. This was consistent with Adam Smith’s vision in *The Wealth of Nations* (1776), and with Alexander Hamilton’s *Report on Manufactures* (1791) to the US Congress, but it was in sharp contrast to the views of the Physiocrats, who in mid-eighteenth-century France had formulated the first holistic economic theory. This theory was propounded by Francois Quesnay in his *Tableaux Economique* (1759) and developed further by Baron Turgot, Minister of Finance to Louis XVI from 1774 to 1776. The Physiocrats argued that national wealth derived solely from agriculture, or more generally from extractive activities, including mining, fishing and arboriculture, so that the only productive class in society was made up of those citizens working in the extractive sector. Merchants, including factory owners and industrialists,

artisans and even wealthy landowners, were 'sterile' in that they generated no net wealth themselves, but only repackaged and redistributed the wealth created by the extractors.

Adam Smith's economic vision, by contrast, was one in which trade and industry did indeed create wealth. Within twenty-five years of the publication of *The Wealth of Nations*, wealth created by technologically transformed industries in England and Western Europe was beginning to transform society. In his *Letters to an Inhabitant of Geneva* (1802), Saint-Simon argued that France's future prosperity depended on optimizing industrial production. To do that, French society needed to be reorganized so as to reap the benefits from an industry-driven, rather than an agriculture-driven, economy. Saint-Simon proposed the creation of a European committee of twelve scientists and nine artists to guard 'civilization' as this transition was made. He also called for a Council of Newton, composed of twenty-one scientists, the 'Elect of Humanity'. These men and women were to be nominated by, and supported by contributions from, the public to ensure that they were apolitical. Their task was to do research and to oversee a new scientific religion that Saint-Simon saw as central to a 'modern' society.

Seventeen years later, in his book *Social Organization*, Saint-Simon called for the creation of a new parliament comprising three chambers: a chamber of invention, composed of scientists, artists and engineers; a chamber of examination, composed of scientists only; and a chamber of execution, composed of leaders of industry. In a society whose well-being depended on optimizing industrial production, scientists and industrialists would be, for Saint-Simon, the 'natural leaders' of the working class, and a new political system was needed that reflected that reality. It followed that industrialists should replace the feudal and military classes in government, because the business of government was ensuring a social order that allowed for an optimal industrial-entrepreneurial environment.

Like Francis Bacon, who had argued early in the seventeenth century for mass education in the technical arts informed by his version of natural philosophy, Saint-Simon had no significant knowledge of science and even less of engineering. Both men were social reformers who had visions that science and technology could drive a nation's wealth and security. Unlike Bacon, however, Saint-Simon's vision was informed by his witnessing the beginnings in his lifetime of what he correctly foresaw would become a flood-tide of industrial development, driven by successive technological innovations that drew on scientific knowledge. If France were to manage the shift to such an industrial economy successfully, traditional politics, social organization, social systems and personal as well as social values needed to be replaced by new ones that reinforced science serving the needs of industry.

Saint-Simon could do no more than sketch what those new systems and values would be like, but his ideas reached a wide audience, especially among students at the *École Polytechnique*. Some of these students did subsequently influence French industrial policies, playing roles in the creation of the *Credit Mobilier* bank to finance industrialization and in the promotion of grand engineering projects like the Suez Canal, but the direct impact of Saint-Simon's ideas was modest. Their indirect impact, however, through the writings of Auguste Comte, was considerable.

Comte was thoroughly literate in the science and engineering of his day. Before serving as Saint-Simon's private secretary and assimilating his ideas, Comte had been a student at the *École Polytechnique*. Although he was ultimately expelled for his political activities, Comte received an excellent education in science-based engineering at a time when the *Polytechnique* was the leading engineering educational institution in the world, pioneering engineering education based on science, mathematics and the laboratory instead of the machine shop and field

experience. Especially in his *Course of Positive Politics* (1851–1854), Comte presented by far the most detailed plan yet for creating a new society whose well-being would be driven by science applied to industry, with the parallel goals of order and progress.

Progress, Comte claimed, would come from the continuing growth of ‘positive’, that is, empirical, fact-based, knowledge via Bacon’s experimental method, and its application by engineers to newer and better products and production technologies. Order would be preserved by a political system anchored in a science-reinforcing ‘rational’ religion. The values of this religion, inculcated into citizens from birth, would constrain not only the behaviour of the worker masses, but also the behaviour of the governors of society, ensuring that their decision-making would always be in the best interests of society rather than of the industrial elite alone. The key was for the governors to use the methods of ‘positive’ science – which for Comte always meant applied science, science stripped of metaphysical, merely theoretical, pretensions – to make political decisions.

Comte’s new political system was openly hostile to parliamentary democracy, as was Saint-Simon’s. For both, transposing the ‘infallibility’ of science to society entailed creating an elite ruling class. This was justified for them by the promise of continually improving the well-being of all citizens by optimizing the production of wealth by industry. This, in turn, required optimizing the ability of engineers to apply the growing body of scientific knowledge, and employing the methods of science and engineering in politics and in ethics. Scientists and engineers were to be core members of the ruling class, whose task was to maintain social order while enabling technology-driven progress given the continual social changes that progress entailed.

These plans of Saint-Simon and Comte did not erupt out of a vacuum. They were an extension of a broad eighteenth-century perception that the ‘new philosophie’ of nature created in the seventeenth century, what we call early modern science, could be, and needed to be, an agent of social reform. Already in the seventeenth century Hobbes, in *Leviathan* (Chapter 30), had called for using Galileo’s method to make political philosophy scientific, and John Graunt, William Petty and Edmond Halley had begun the collection of social statistics for the express purpose of developing more effective public policies in the areas of trade and of government-issued annuities. In Part IV of *The Art of Conjecture* (1713), Jakob Bernoulli introduced the application of probability theory to ‘Civil, Moral, and Economic Matters’, including judicial reasoning and public policies. Both Turgot and his protégé the Marquis de Condorcet promoted probability theory as a rational basis for the design of social institutions. Turgot prepared for Louis XVI a ‘rational’ taxation policy (which led to his dismissal as Finance Minister!) and in 1785 Condorcet published *Essai sur l’application de l’analyse a la probabilité des décisions rendue a la pluralité des voix*, containing important theorems on jury and political voting procedures. Condorcet’s ‘voting paradox’ is an example of his use of mathematics to determine public policy, namely, the voting process he was to recommend for the Revolutionary constitution. He was able to show that under quite plausible circumstances, voters ranking as few as three candidates would generate equally objective but non-unique outcomes, that a two-stage voting process could easily lead to an outcome the majority of voters did not prefer, and that voting was sensitive to the order in which choices were posed. (The so-called Impossibility Theorem of the mid-twentieth-century economist Kenneth Arrow is a more sophisticated version of Condorcet’s voting paradox, one that lends itself to showing the inevitably non-unique character of ostensibly objective engineering design trade-off decisions.)

These are particular instances of a more general intellectual development in the eighteenth century: the claim that the new science of Newton *inter alia* was comprehensively applicable to human affairs. There is something paradoxical about this claim in that the new science, whether in its Galilean, Cartesian, Newtonian or Leibnizian form, was rigorously deterministic. But if reality, personal and social no less than physical, is deterministic, how can it be deliberately, wilfully, *reformed*? Nevertheless, the perception that the new science was successful because it epitomized reason, and that it was applicable to human affairs, was the foundation on which claims of Enlightenment and the Age of Reason rested.

For example, although Comte introduced the term 'sociology', Montesquieu had already effectively founded social 'science' in *The Persian Letters* (1721) and *The Spirit of the Laws* (1748). In these books, Montesquieu naturalized social institutions and values, bringing them within the scope of scientific inquiry and explanation. Between 1772 and 1791, Gottfried Herder developed a naturalistic, comparative cultural anthropology, reintroduced to a more receptive audience Giambattista Vico's earlier *New Science* (of cultural evolution) and published a *Dissertation on the Reciprocal Influence of Government and the Sciences* (1780). Naturalizing the economy as a reality amenable to scientific and eventually mathematical analysis was another eighteenth-century innovation. It is reflected in the essays on economic issues of David Hume, in the programme of the Physiocrats, in Adam Smith's *Theory of Moral Sentiments* (1759) as well as in his *Wealth of Nations*, and early in the nineteenth century in the very influential writings of David Ricardo, contemporary with Saint-Simon.

Hume followed Hobbes and Locke in formulating a naturalistic theory of knowledge, based on a scientific understanding of how the mind works. For Hume, this meant seeking a 'Newtonian physics' of the mind. The Abbe Condillac's writings triggered a movement whose members pursued a scientific psychology, after millennia of speculative philosophical psychology. Politics and ethics, it was argued, needed to reflect the reality of human beings in the physical and social world, as revealed by science. This was a founding principle of the American and French Revolutions, and of the English Reform movement. Denis Diderot's *Encyclopedie* project was, as the authorities well understood, subversive, and intentionally so. Diderot wanted to provoke social change by making technological no less than scientific knowledge available to all, hence the inclusion in the *Encyclopedie* of eleven volumes of illustrations of technical processes. Diderot was motivated to emphasize technology by his concern that the new science and the new mathematics were, by the late eighteenth century, becoming too abstract and too esoteric, at the expense of being useful to society.

This was the context out of which the social re-engineering programmes of Saint-Simon and Comte sprang. In fact, Western European, American and, from 1868, Japanese societies *were* transformed in the course of the nineteenth century, but the transformation was not along Saint-Simonian or Comtean lines, and not at all the product of thoughtful re-engineering. Changes in policies, institutions, organizations and values resulted from piecemeal accommodations to the needs of new vested interests created by new forms of production and commerce. The new form of greatest impact, perhaps, was the centrally administered, hierarchically organized, vertically integrated industrial corporation. The explosive growth of these enterprises was wholly dependent on new production, communication, transportation and information technologies. These technologies, in turn, created the need for unprecedented numbers of science- and mathematics-trained engineers as employees, and for scientists and mathematicians to train them. It was in the context of optimizing the operation of these corporations that efficiency became a core value for business, and through business for society.

Frederick Winslow Taylor's 'scientific' analysis of work was the approach of a modern engineer to optimizing operations and workflow in a factory treated as a system (Kanigel, 1997). The obvious conclusion to be drawn from Taylor's studies was that engineers should be in charge of industrial corporations, not financiers and lawyers. Taylor's rationale for industrial leadership by engineers was preceded by Thorstein Veblen. In his *Theory of the Business Enterprise* (1904), Veblen had argued that capitalist-driven business was dominated by the pursuit of profit, with no concern for the well-being of society. New technologies, however, had the potential to improve all of society, if only they were developed and their benefits distributed to that end. If engineers were in leadership positions, Veblen wrote, they would use their commitment to specifically engineering values – accuracy, precision, efficiency and successfully meeting goals – to benefit society rather than to make profit the primary goal of industrial operations.

Veblen repeated these ideas in *The Engineers and The Price System* (1921) and in his last work, *Absentee Ownership and Business Enterprises in Recent Times* (1929). The economy, he argued, needed to be managed as one would manage an efficient machine. This entailed putting engineers in charge of the economy, not profit-driven businessmen. On a more abstract plane, Max Weber's *The Protestant Ethic and the Spirit of Capitalism* (1905), but even more so his *The Theory of Social and Economic Organization* (English translation 1947, but only part of a larger work that evolved between 1915 and 1925) independently reinforced Taylor's and Veblen's focus on the overriding value of efficiency in modern societies. Weber argued that rationality based on efficiency, defined techno-scientifically, was the core value of modern, industrial capitalist society. There was, therefore, no practical possibility that capitalists would cede control of wealth-creating businesses to anyone other than managers made in their own image. Jacques Ellul extended Weber's point in his highly influential *La Technique ou l'Enjeu du Siecle* (1954; in English, *The Technological Society*, 1964). Ellul argued the fundamentally anti-human character of technical rationality and his book stimulated a broad critique in the United States and in Europe of the roles of scientists and engineers as enabling contemporary social policies by providing technical expertise to political and economic elites.

In parallel with these intellectual/theoretical analyses, the publics in societies that were being revolutionized by technology-driven industry were acutely aware of how their personal and social lives were being transformed, and by whom. From the second half of the nineteenth century right through the Great Depression of the 1930s and into the post-war period, hundreds of popular novels, plays and films explored the roles of engineers and scientists in driving social change, typically by serving the interests of entrepreneurs and financiers (Goldman, 1989). Some of these works treated engineers and scientists heroically, some as pawns manipulated by capitalists. Some works were utopian, some were dystopian. Some, like the film version of H.G. Wells' *Things to Come* (1936), began as engineer-led utopias but ended as dystopias. Earlier, Fritz Lang's film *Metropolis* (1925) depicted an attempt by capitalists to annihilate the human working class in favour of robots developed for the capitalists by a 'mad' scientist. Lang's film echoed Karl Capek's play *R.U.R.* (1920), which introduced the term 'robot'. In *R.U.R.*, and in his novel *War with the Newts* (1936), humans are conquered by sentient servants created for humanity by scientists and engineers. Rene Claire's film *A Nous la Liberte* (1931) had a screenplay that might have been written by Veblen, and Charlie Chaplin's *Modern Times* (1936), which borrowed from Claire's film, mocked the inhumanity of technologically defined modernity.

With the onset of the Great Depression, Veblen's ideas about industrial leadership by engineers were taken up by Howard Scott and M. King Hubbert. In 1931, they created

Technocracy Incorporated, an organization whose goal was to put the economy under the control of scientists and engineers who would implement a thermodynamics-based economic model keyed to energy efficiency, rather than to money (Meynaud, 1968). Although popular for a while, the movement that Scott and Hubbert hoped to precipitate never formed. William Akin, in *Technocracy and the American Dream* (1977), attributed this to the failure of Scott and Hubbert to articulate a believable political plan for accomplishing their goal, but it is also the case that every attempt to organize American engineers politically has failed.

What can we learn from this very brief survey that is relevant to our question of whether engineering reasoning can help us to design more effective social systems and public policies?

First of all, that the idea of applying to what Dewey called 'social interests and affairs' the scientific method and knowledge generated by that method is as old as early modern science itself, long preceding the experience of industry-caused social change. It follows that looking to science and/or engineering for more effective, because more rational, social systems and policies is not uniquely a reaction to the world situation today. Rather, the situation today has resurrected a recurring perception that the successes of science and of engineering are the result of subjecting experience to systematic, logical reasoning. The argument is as follows: science and engineering are undeniably extraordinarily successful in solving the problems they choose to address; this success is the result of following a well-defined, logical reasoning process; so, we as a society should be able to solve social problems by adopting that same process.

It is not at all clear, however, that there *is* a single method in accordance with which scientists reason. On the contrary, a great deal of evidence has accumulated that there is no single form of reasoning, no one method used by all scientists even within a single discipline, let alone across all disciplines. Furthermore, it has become increasingly clear that engineering reasoning is different from scientific reasoning, though engineering practice has been subject to much less study by historians, philosophers and sociologists than the practice of science.

A second lesson is that it was only in the nineteenth century that engineering was recognized as necessary, *along with science*, in order to realize the idea of making social systems 'rational'. By the early twentieth century, however, engineering increasingly seemed the *primary* model for rational management of social institutions, even as engineering increasingly incorporated knowledge generated by scientists. It was through engineering that inventions were turned into innovative technologies, as engineers selectively exploited scientific knowledge and stimulated the production of new engineering know-how, in order to solve the problems posed by bringing innovations into the marketplace. The result is that it is reasonable today to conclude that it is the way that engineers solve *problems* that society should adopt in order to develop more rational social systems, and not the way that scientists generate *knowledge*. The world we live in is directly the result of the form in which technological innovations were introduced into society and disseminated, a process in which engineering problem-solving played a pivotal, enabling role. Understanding how engineers play this role seems much more likely to provide a model for solving social problems than the process by which scientists produce idealized, universal theories explicitly removed from their social context.

Finally, we can learn from history the fruitlessness of any attempt at shifting political or managerial power to engineers or scientists and away from entrepreneurs (who may themselves be engineers or scientists), financiers and non-technically trained politicians, managers

and bureaucrats. History and common sense strongly suggest that is not going to happen: power has more inertia than matter!

Our question thus becomes: Is there a method of reasoning employed in engineering practice that can be abstracted and applied by non-engineers to develop more effective social systems and public policies? Engineers would surely play a consultative role in such efforts, but as methodology mentors only.

1.3 Science and Engineering: Distinctive Rationalities

Scientists pursue understanding of natural and social phenomena. In the process, they generate what they call ‘knowledge’. For the overwhelming majority of scientists, the object of this knowledge, what it is about, exists independently of the cognitive process. What scientists claim to know is the way that things are, independently of human experience and, in principle, independently of the human mind, individual or collective. This is the essence of scientific realism: a scientific knowledge claim is true, is validated as knowledge, by its correspondence with the way things ‘really are, out there’. Even the minority of scientists who claim not to be realists claim that what they know transcends experience: there may not, for them, *be* black holes ‘really’, but there really *is* a stable pattern ‘out there’ that is revealed in experience and that corresponds to what we call a ‘black hole’. These patterns are facts that are *revealed* in experience, but are not *produced* by experience.

From its seventeenth-century beginnings to the present day, science has been quite explicit that it was simultaneously empirical and, so to speak, trans-empirical; that it was rooted in experience but sought to disclose an unexperienced, indeed an unexperienceable, reality underlying experience and causing it. What its founders claimed distinguished modern science from Renaissance magical nature philosophy, which made the very same claim, was its use of a subject-neutral, objective method that reliably – fallibly and corrigibly, but reliably nevertheless – linked experience to its unexperienced causes.

Francis Bacon formulated an inductive, experimental, non-mathematical version of this method. Descartes formulated a deductive, mathematical version in which experiment played a very limited role. Galileo formulated a third version, modelled after his reading of Archimedes, that was intensively experimental but also intensively mathematical and deductive. Newton called himself a Baconian but was closer to Galileo and even to Descartes, protestations to the contrary notwithstanding. Newton described his method as analysis/decomposition followed by synthesis/recomposition, success in the latter alone qualifying as understanding. But Newton also understood that the method a scientist used – the term ‘scientist’ is anachronistic until the 1830s, but easier to use than ‘natural philosopher’ – resulted in idealizations that did not correspond to the way things ‘really’ were, which is, of course, not revealed in experience but only in the mind, through calculation, which brings empiricism perilously close to rationalism.

What Newton and all his fellow scientists *did* share, methodologically, was a deep commitment to the non-subjective and value-free character of scientific reasoning. The logic of this reasoning was, in practice, fuzzy: a mix of induction, deduction, intuition, guesswork, serendipity and even some wishful thinking. Nevertheless, the self-professed goal of modern science has been and remains to describe nature as it is and to understand natural phenomena by providing an explanation of how nature works as a consequence of what its fixed properties are.

At the same time, and from its inception, modern science has been deeply conflicted about the status of its knowledge claims, and this conflict affects the usefulness of applying scientific reasoning to human affairs. As revealed by the rhetoric of science, from Bacon to the present day, scientific theories are said to describe a universal reality that transcends human experience, but which somehow is accessible to reason, even though reason seems limited to experience, which is particular. Scientific knowledge is said to be universal, necessary (because constrained by an independently existing reality) and capable of certainty (if it gets reality right), but it is dependent on experience, which is contextual, contingent and never certain.

The conflict lies in scientists recognizing that logic precludes claims that scientific knowledge is universal, necessary and certain, even in principle, and precludes having as its object an experience-transcending reality, while at the same time wanting precisely that to be the case. The only route to certainty is by reasoning deductively, but reasoning that begins with experience is ineluctably inductive, and it is no secret that there is no way of logically bridging the gulf between induction and deduction. That the experimental method cannot bridge this gulf was well known in the seventeenth century, as committing what some logicians call the 'Fallacy of Affirming the Consequent' and others the 'Fallacy of Affirming the Antecedent'. Christian Huyghens, for example, in the preface to his *Traite de la Lumiere* (1690), wrote that logically, experiments can never establish a necessary connection to an underlying cause, but when an experiment confirms a theory's predictions, especially in surprising ways, how can we not conclude that truth has been revealed to us! In this regard, Bacon was just as insistent as Descartes that following his method would lead to knowledge of reality. Galileo claimed that what we knew about nature by the deductive Archimedean method we knew in the same way that God knew, though of course God knew infinitely more. For Newton, the goal of his physics was to discover the 'true causes' of natural phenomena, not merely hypothetical, logically possible causes.

This continuing conflict within modern science over the nature of scientific knowledge, implicating the status of its knowledge claims and its trans-experiential object, echoes an ancient philosophical conflict. In his dialogue *The Sophist* (246a *et seq.*), Plato wrote of a perennial battle between the Sky Gods and the Earth Giants over the nature of knowledge. For the Sky Gods, the object of knowledge was an ideal, universal, timeless reality and knowledge was universal, necessary and certain, fundamentally different from belief and opinion. For the Earth Giants, the object of knowledge was the material world encountered in concrete, mutable experience and knowledge was a species of belief, thus particular, contingent and probable only. The (Platonic) philosopher was an ally of the Gods and pursued their version of knowledge. The allies of the Giants and their version of knowledge called themselves philosophers, but for Plato they were merely sophists, *knowing* nothing. Modern scientists clearly allied themselves with the Gods and Plato's philosophers in pursuing idealized knowledge for its own sake, even as they fraternized with Giants to collect data and perform experiments. Engineers, however, are wholly on the side of the Giants and the sophists. They are not interested in knowledge for its own sake, but in knowing for the sake of doing (Goldman, 1990).

Engineering and science are both intentional activities, but the intentionalities could not be more different. The intended object for science is understanding; the intended object for engineering is action. The rationality of science is the reasoning that results in claims of understanding and providing explanations. This reasoning is explicitly value-free, though implicitly it incorporates what philosophers of science call epistemic values ranging from honesty to employing assumptions that are not logical consequences of data. The object of scientific

reasoning is assumed to be independent of the reasoning process, antecedent to the reasoning process and unaffected by that process.

The rationality of engineering, in contrast, is the reasoning that leads not to abstract knowledge, but to a kind of knowledge-enhanced know-how, the reasoning employed to solve a particular problem. As such, engineering reasoning is explicitly and inescapably valuational. Values are intrinsic both to the definition of an engineering problem and to what will constitute an acceptable solution to that problem. The rationality of scientific reasoning is measured by the conformity of the results of that reasoning to a supposed antecedent and independent state of affairs, called nature or reality. The rationality of engineering reasoning is measured by whether the results of that reasoning 'work', as judged relative to a set of highly contingent and very subjective value judgements. Furthermore, the object of engineering reasoning does not exist independently of that reasoning process, and it is very directly affected by that process because it is created by it!

Paraphrasing Theodor von Karmann, if science aims at revealing what is, engineering aims at introducing into the world what never was, for the sake of acting on the world in new ways. As Ortega Y Gasset argued in *Towards a Philosophy of History* (1941), this is not reducible to responding to physical necessities only. Today, as in remote antiquity, engineering the world is overwhelmingly a matter of projecting imagined possibilities onto a world that lacks them, and then making those possibilities actual. Engineering the world begins with simple tools and weapons, but advances to controlling fire and creating shelters and clothing, metals and ceramics, rafts and boats, new, unnatural kinds of animals and plants, fortified cities, monumental buildings, canals, irrigation systems. By the time writing was invented in the fourth millennium BCE, thousands of years of complex yet reliable know-how had accumulated and afterwards continued to accumulate, growing in complexity and scope, largely indifferent to writing.

Where is the dividing line between craft know-how and the kind of know-how that we recognize, after the fact, as representative of engineering? How did people acquire know-how? How did know-how cumulate and evolve over centuries and millennia without writing? We have a common-sense idea of how know-how is taught, by apprenticeship, but this does not explain such accomplishments as breeding dogs from wolves, wheat from wild grasses, or cultivable rice from wild rice, projects that took centuries of sustained, intentional effort. Animals have know-how, but human know-how is unique for being cumulative, adaptive and imaginative. Finding answers to questions about know-how, and thereby illuminating the engineering dimension of human beings in the world, has been ignored by Western philosophers, including natural philosophers, in favour of an obsession with abstract knowledge (Goldman, 2004). (What I mean by know-how here is very different from the philosopher Gilbert Ryle's term 'knowing-how'. Ryle's 'knowing-how' serves an epistemological function, fitting into his theory of knowledge. Know-how for me is ontological. It is a highly specific, and typically complex, form of doing or making, for example, making glass or breeding animals and plants or building a sailing ship. Historically, engineering as we use that term emerged when knowledge was applied to know-how. Perhaps the earliest explicit reference to doing this is in the opening chapter of Vitruvius' *On Architecture* (approximately 15 BC). The idea was revived in the Renaissance and was consciously pursued by self-styled engineers through the seventeenth and eighteenth centuries to the momentous convergence of engineering and the newly powerful scientific theories in the nineteenth century that generated the world we live in today.)

Elias Canetti put the subordination of engineering to science in Western culture this way: 'Among the most sinister phenomena in [Western] intellectual history is the avoidance of the concrete. [Thinkers] have had a conspicuous tendency to go first after the most remote things, ignoring everything that they stumble over close by' (Canetti, 1984, p. 14). But 'remote', abstract, knowledge, as Aristotle who embraced it acknowledged, is incapable of determining action, because action is always concrete, contextual and temporal. Aristotle concluded that action is determined by desire, desire shaped by experience-based beliefs and opinions, and at best informed by knowledge, but always and only initiated by desire. Engineering, which overlaps what Aristotle called 'praxis' and what he called 'art' (action consciously informed by established know-how), is decisively inferior to science/knowledge on this view, precisely because it is action-focused and lacks the universality, necessity and certainty of knowledge.

1.4 'Compromised Exactness': Design in Engineering

It seems clear enough, then, why the reasoning scientists employ in producing scientific knowledge is not going to be a model for formulating action plans. The knowledge itself may be useful, but not the reasoning process by which it was produced, whatever that process is, precisely. Scientific reasoning explicitly excludes the kinds of value judgements that are integral to action. And acting on the basis of scientific knowledge must be qualified by recognizing that it is corrigible and fallible. Scientific theories are continually evolving, continually being modified as new data are acquired, as new experiments are performed, as new instruments are invented, leading to new explanations of the same phenomena and to new theories based on new assumptions. But what about the reasoning process that engineers employ to produce solutions to engineering problems?

Engineering reasoning *always* subserves action and thus is intrinsically value-laden. On the face of it, then, engineering reasoning may well be a model for designing social systems and formulating public policies, both of which aim at action. Note, however, that the distinctiveness of scientific and engineering reasoning is ideal. As practices, science and engineering overlap in employing similar problem-solving modes of reasoning. Scientists, especially experimental scientists, look very much like engineers as they design, adapt and integrate equipment to create projected experimental situations that will generate anticipated data. Inevitably, individual pieces of equipment and the experimental setup as a whole require 'tinkering' that is pulled by the intended object of the experiment, its intended outcome, which thus acts like an Aristotelean final cause: the experimental setup exists in order to produce a specific outcome. That is, the anticipated outcome 'pulls' the conception of the experiment, its design and its execution, especially the judgement that it 'worked'.

The recent announcement that the Large Hadron Collider had revealed the existence of the Higgs boson, a logical consequence of the prevailing Standard Model of quantum physics, is an example of this. The machine was designed and built as dictated by the prevailing theory in order to produce the Higgs boson, and it did. At least, its operation was interpreted via specialized computer-based analysis as having produced Higgs bosons, albeit very few of them. Had they not been produced, scientists would either have had to modify their theory, search for a new theory, or decide that the Large Hadron Collider was not working properly or not up to the job. The latter conclusion was reached in the case of the failure of the \$400 million Laser Interferometer Gravity Observatory to detect the gravity waves predicted by the General

Theory of Relativity and so was modified, at considerable additional expense, and then it did do the job!

In its experimental mode, science as a practice implicitly *seems* very much like engineering, but without the explicit wilfulness and extra-technical value judgements that are central to engineering. For their part, engineers are often said to employ scientific reasoning when they engage in experimental testing of designs, acquire and keep systematic records of data, and modify designs in light of that data. This is, however, a popular and misleading use of the term ‘science’, as technologists even in remote antiquity did the very same thing as they created bodies of sophisticated know-how. There is thus a form of problem-solving reasoning on which both science and engineering build, but which precedes both, logically and historically.

The distinctiveness of engineering *vis-à-vis* science is most clearly revealed in the design process, understanding ‘design’ as that facet of engineering practice that produces a specification of the terms of a problem together with criteria of *acceptable* solutions to that problem. Both of these require multiple complex value judgements centred on what someone wants the outcome of the design process to *do*. The outcome of the design process is not the revelation of a pre-existing state of affairs as in science, but an act of creation. What engineers enable is an outcome determined by the wilfulness motivating a desire for what some outcome must do and how it needs to do it. The problems that engage scientists are ‘there’, waiting to be recognized. Engineering problems, by contrast, are created by people who *want* to do something specific and are constrained in various ways, to a degree by what nature will allow, but primarily by highly contingent factors that, from a logical as well as a natural perspective, are arbitrary: time, money, markets, vested interests and social, political and personal values.

It follows that engineering reasoning in the design process is in a sense ‘captive’ to the wilfulness underlying the specification of engineering problems and their solutions (Goldman, 1991). This makes the reasoning employed in engineering problem-solving profoundly different from that in scientific problem-solving. Since the early nineteenth century, however, engineering has become increasingly dependent on scientific knowledge, lending support to the claim that engineering is ‘merely’ applied science. But engineers deploy scientific knowledge selectively, on terms dictated by the criteria of the engineering problem and the solution specifications. These criteria reflect complex, contingent and competing value judgements that have nothing to do with technical knowledge and are beyond the control of the engineers engaged in the design process. There is, therefore, a profound gulf between engineering and science, as profound a gulf as the one in logic between inductive and deductive inference. Engineers selectively employ scientific knowledge on terms dictated by the requirements of solving engineering problems as scientists selectively deploy mathematical knowledge on terms dictated by the requirements of solving scientific problems. Engineering is no more *just* applied science than science is *just* applied mathematics.

In the course of creating a new science-based engineering curriculum for the University of Glasgow in 1855, one that justified distinguishing engineering education from the existing science education while still linking engineering to science, William Rankine, eminent in science and in engineering, characterized the reasoning underlying engineering practice as ‘compromised exactness’ (Channell, 1982). The exactness in engineering came from its utilization of experimentally validated scientific knowledge. Such knowledge was exact because it was universal, abstract and deductive, as in the then prominent Lagrangian version of Newtonian mechanics, Fourier’s mathematical theory of heat and the new science of thermodynamics.

But what makes something engineering, and not merely applied science, is that the *application* of exact technical knowledge was ‘compromised’ by commercial considerations of economy and efficiency. If scientific knowledge was, as it claimed to be, objective, then engineering, in spite of utilizing scientific knowledge, was not objective in the same sense, and could even be said to be subjective, because it incorporated person- and situation-dependent value judgements. What Rankine meant by ‘compromised exactness’, then, goes to the heart of the distinctiveness of engineering *vis-à-vis* science.

Engineering cannot be derived from science because application, by its nature, is constrained by explicitly contingent value judgements. That’s what Rankine meant by characterizing engineering as ‘compromised’ exactness; not that engineering is simply approximate, while science is exact, but that engineering is inescapably wilful, valuational and contextual. Engineers are challenged to build *this* bridge, for *this* purpose, in *this* place, within *this* budget and in *this* time frame. Engineers need to design an airplane engine, an automobile transmission, a computer that satisfies a specification that is virtually never driven by what the engineers consider the best possible design given their technical knowledge, but by one among many possible interpretations of what is judged best in a particular situation by individuals committed to highly contingent commercial or political agendas.

The IBM PC, for example, back in 1981 was in no way the best ‘personal’ computer design possible then, from an engineering perspective, but its commercial success justified its ‘compromised’ character: selectively applying available technical knowledge on behalf of IBM management’s interpretation of projected market opportunities. Tracy Kidder (1981) exposed the very same ‘compromised’ character of engineering in the design of a highly successful mini-computer that saved the Data General Corporation (for a while). The same kind of ‘compromising’ is revealed in the designs of the US Space Shuttle (Logsdon, 2015), the International Space Station (Logsdon, 1998), and indeed of everything from weapons systems to consumer products that engineers enable bringing into existence. Sometimes the ‘compromised’ design is successful and sometimes not, but success or failure has less to do with the technical knowledge employed than with the value judgements constraining the application of that knowledge. The Segway is a case in point: technically brilliant, but a marketplace failure, relative to its inventor’s, and its investors’, expectations (Kemper, 2003). In the case of Apple’s iPod, iPad, iPhone and iWatch, marketplace success followed not from technical excellence, but from managerial judgements of what the finished product needed to look like, what it would do and most importantly, *how* it would do what it would do compared with what competing products were doing.

Rankine’s characterization of engineering as distinctive because it is ‘compromised exactness’ thus finds its clearest expression in the engineering design process, because that is where problems and acceptable solutions are defined by the introduction of contingent value judgements. But if the design process is the essence of engineering, then the essence of the design process is trade-off choices among the many natural and contingent parameters that comprise the technical specification of the design problem and its acceptable solution, with an emphasis on ‘acceptable’. The term ‘technical’ here disguises a host of very non-technical and subjective value judgements. In the case of physical products, for example, these would include trade-offs among manufacturing cost (which implicates the materials to be used and the suppliers), size, reliability, safety, longevity, serviceability, performance, appearance, ease of use, compatibility with related products and services, compliance with relevant laws and regulations, scale of production, scalability of product and its modifiability, time to market, and market

niche and marketability (given existing products and services). Services and software designs would generate a similar list of trade-off choices.

It is in trade-off choices that the wilfulness underlying engineering problem-solving emerges. What engineers know, and what they can adopt and adapt from relevant pools of engineering know-how and scientific knowledge, certainly influences what they can do as engineers to solve technology-related problems for people (Vincenti, 1990). This knowledge influences the negotiations eventuating in a well-defined problem and its acceptable solution, but it does not determine that outcome. From the perspective of engineering, problems and possible solutions are wildly over-determined: there are too many possibilities, and the ones that engineers would prefer on engineering grounds typically are not the ones that management prefer!

Attempts at reducing the subjectivity of trade-off decisions by means of an objective, and thus 'scientific', formal methodology have been numerous. They include: Analogy-Based Design; Analytic Hierarchy Process; Suh's Axiomatic Design; Decision Matrix Techniques; General Design Theory; Quality Function Deployment and the House of Quality; IDEF; PDES-STEP; PERT charts; Pugh Concept Selection; Taguchi's Theory of Robust Design; DYM; PYM; TRIZ; and many more. The sheer number of theories and commercial products that claim to make trade-off choices objective alone suggests that none of them do the job. For any given design team, however, one or more of these will be helpful, and some tool for managing a large number of mutually implicating decisions is close to a necessity. In the end, however, wilfulness and subjectivity are ineluctable features of trade-off decision-making, and therefore of the design process, and therefore of engineering reasoning and practice. This conclusion is supported by arguments that it is not possible to generate a unique ranking of three or more parameters, each of which has three or more possible states or values. Among these arguments are Condorcet's voting paradox mentioned earlier and Kenneth Arrow's 'Impossibility Theorem' (Arrow, 1951). The ranking process may be quantitative and thus apparently objective, but there are no unique outcomes, and at least some of the ranking weights must be subjectively assigned. How much weight should be assigned to size, weight, reliability, specific materials, certain performance features compared to others, cost of production, ... [An analogous problem exists with assigning prior probabilities in Bayesian probability theory: once assigned, the probabilities generated are strictly objective, but no one has yet come up with a process for assigning prior probabilities objectively, though many have tried.]

1.5 Engineering Social Systems?

The upshot of all this is that there is a strong similarity between the engineering design process with its trade-off choices and the process by which social institutions are created and public policies are formulated. Both are political processes in the sense of being framed and determined by irreducibly subjective, highly contingent and competing value judgements. If this is indeed the case, then how could engineering reasoning contribute to designing better social systems and formulating better public policies? Not, obviously, by transforming the latter into an objective process. But the 'logic' of the engineering design process shares with the social system design process the goal of a functional accommodation among multiple competing and value judgements. In the case of engineering, however, all of the value judgements that determine the specification of problems and solutions are explicit and subordinated to the functionality

of the projected outcome. As a result, and in spite of the irreducible subjectivity of the process, the process generates objective metrics for assessing whether the outcome works as anticipated.

This clearly has not been the case historically with social systems and public policies. These, too, are the outcomes of negotiated design processes, but the outcomes of those processes typically are keyed to satisfying holders of the contending value judgements that their interests have been served. And the contending value judgements are often disguised or misrepresented as facts. In the end, the historical process results in an outcome that satisfies the interests driving the trade-off process and is only loosely coupled to the functionality of that outcome for the public as a whole.

This is the reverse of Dewey's 'experimental method', the methodology of engineering, in which means have no value in themselves but only insofar as they subserve explicit ends and are measured by their effectiveness in doing so. In social system and public policy design, the value judgements underlying the selection of means do have value in and of themselves. They have value to the special interests shaping the design process, and they even shape the end so that it reflects those interests. If the design of social systems and public policies required making explicit the criteria for assessing the outcome as successful, along with the trade-off judgements made to achieve that outcome, then there is every reason to believe that systems and policies would be improved.

But adopting the form of its design and trade-off processes is not all that engineering can contribute to creating improved social systems and public policies. The design process as described here captures the essence of what makes engineering *reasoning* distinctive *vis-à-vis* scientific reasoning. But reasoning is only one dimension of engineering *practice*, which is also essentially experimental and evolutionary. The outcome of the design process needs to be implemented, it needs to be produced and it needs to be used. Implementation reveals that the engineering design process is open-ended. Unlike the deductive inferences drawn from a scientific theory, design solutions can never be guaranteed to work successfully, as judged either by the engineers themselves or by their employers. In this sense, engineering practice is experimental (Petroski, 1992, 2012).

Implementation of design problem solutions generates ongoing feedback into both the solution and the problem. The feedback may reveal weaknesses in the solution that require reassessment of the trade-off choices made and a redesign. But feedback from practice may require reassessment of the problem itself, along with reconsideration of what *now* constitutes an acceptable solution to it. Especially when the design problem involves a new technology, use typically stimulates unanticipated applications that may require modification of the original solution, but always generates new design problems in order to exploit new action opportunities enabled by these applications, or to prevent or manage them. In this sense, engineering practice is evolutionary in the biological sense of having an unpredictable dimension to it. We are witnessing this phenomenon today in the continuing evolution of semiconductor-based technologies and their coupling to the evolution of the Internet, from its initial implementation as an esoteric DARPA-funded project to its extraordinary global penetration of personal, social, economic, political, cultural and professional life. But the Internet is, in this evolutionary respect, typical of engineering design projects. Consider the reciprocally influencing technical and social impacts of the implementations of the steam engine, the gaslight industry, the telegraph and telephone, the automobile and electric power (Hughes, 1983; Hunter, 1985; Starr, 2005; Tomory, 2012; Volti, 2006).

The processes by which social systems and public policies have been designed in the past lack the open-ended, experimental and evolutionary character of engineering design driven by feedback from their implementation. For reasons that are external to engineering *per se*, that is, external to engineers simply as possessors of technical knowledge, engineering designs succeed or fail and are forced to evolve. Often this evolution is driven by factors that to engineers are irrational, for example, marketplace factors that value form over function, mere fashionability, advertising-manipulated style for its own sake, a company's need to distinguish its products from competitors, or a strategy of driving sales by generating change for its own sake, claiming to be 'new and improved'. Often, however, the evolution of engineering designs is driven by the 'space' a new design opens for various forms of improvement and by the innate unpredictability of technological innovations.

Once adopted, innovations typically inspire applications that had not been anticipated, analogous to mutations in biological evolution, and these drive the need for newer and new kinds of designs. Again, the Internet is a perfect instance of this evolutionary character of engineering, not at all 'blind variation' but unpredictable nevertheless. [And thus different from at least Donald Campbell's conception of evolutionary epistemology (Campbell, 1960, but see Polanyi, 1962 and Popper, 1972).] The ubiquity today of music streaming, video streaming, social media, photo and video file sharing, and their implications for hardware and software design are obvious. But this was just as true of Edison's phonograph and moving-film projector. The implementation of innovations also can, and typically does, have consequences that are undesirable as well as unpredictable. Death and injury caused by the automobile, its impact on mass transit and the design of cities, and its socio-political and environmental impacts illustrate this. So does the increasingly threatening 'dark side' of the Internet, including pornography, gambling, identity theft, hacking, cybercrime, cyberwarfare and terrorist networks.

By contrast with engineering's explicitly experimental and evolutionary character, social systems and public policies are promulgated *as if* they were definitive solutions to social problems to which personal and social action must conform, rather than tentative, pragmatic solutions that are expected to be modified by the consequences of their implementation. They do not openly incorporate feedback mechanisms that make learning from the implementation process a normal feature of the social systems and public policy design processes. Instead, the politics of these processes virtually precludes incorporating into policy implementation legislation clear metrics for assessing when a policy is meeting its proclaimed goals together with a process for modifying the policy in light of its actual outcomes. In the United States, instances of this would include the Prohibition amendment to the Constitution, the 'War on Drugs', mandatory federal prison sentences, the original Medicare act and its prohibition of negotiating the cost of prescription medications with pharmaceutical companies, the federal student loan programme with no provision for monitoring the consequences of open-ended lending, the Cuba embargo with no provision for assessing its impact on the Cuban people rather than on the Cuban government, the exemption of the fracking industry from the Clean Drinking Water Act, the commitment to NATO with no post-Cold War exit strategy, and many others.

Implicitly, social policies, like engineering designs, *are* open-ended; they are also implicitly experimental and in principle capable of modification in response to feedback from outcomes. The Prohibition amendment, for example, was repealed, but the 'war' on drugs drags on. As the other policy instances listed above illustrate, the political dimension of

social policy-setting precludes keeping the policy-setting process open to modification by feedback from accumulating experience with the policy's implementation. In the world of engineering, it is expected that designs will evolve in light of experience, while in the world of social policy, actors behave *as if* policies were definitive. To be sure, there is a difference between the timelines of engineering design evolution and social policy evolution. It would be counterproductive for policies to be modified too quickly in response to outcomes. Social policies need to promote a sense of stability, a sense that they are not going away, if they are to force, and enforce, changes in behaviour, laws and investment strategies. And there is often a moral dimension to social policies, for example in the case of civil rights legislation, that complicates the process of revising a policy based on its short-term consequences, which included numerous and sustained acts of violence, for example, over school desegregation and busing. It is nevertheless suggestive that modelling social system and public policy design after a *comprehensive* understanding of engineering methodology, one that includes the distinctiveness of engineering reasoning together with the experimental and evolutionary character of engineering practice, has the potential to significantly improve the performance of social systems and the effectiveness of public policies.

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