Why we need a philosophy of engineering: a work in progress

STEVEN L. GOLDMAN

Departments of Philosophy and History, Lehigh University, Bethlehem, PA 18015, USA

Engineering problem solving employs a contingency based form of reasoning that stands in sharp contrast to the necessity based model of rationality that has dominated Western philosophy since Plato and that underlies modern science. The concept 'necessity' is cognate with the concepts 'certainty', 'universality', 'abstractness' and 'theory'. Engineering by contrast is characterised by wilfulness, particularity, probability, concreteness and practice. The identification of rationality with necessity has impoverished our ability to apply reason effectively to action. This article locates the contingency based reasoning of engineering in a philosophical tradition extending from pre-Socratic philosophers to American pragmatism, and suggests how a contingency based philosophy of engineering might enable more effective technological action.

For reasons that have been at the heart of Western culture from its beginnings in ancient Greece, engineering has been treated dismissively by intellectuals and in particular by philosophers.[1] The reasons reflect deeply rooted prejudices that have been sustained for well over two thousand years. Of special relevance to the persistent underestimation of engineering is the low value historically placed by intellectuals on the contingent, the probable, the particular, the contextual and the temporal. Conversely, philosophers especially have placed a high value on the necessary, the certain, the universal, the context independent and the timeless. This hierarchisation subordinates practice, values, emotion and will to theory, value neutral principles and deductive logic in ways that leave us ill equipped to deal rationally with life. Indeed, from the perspective of necessity, life and action are fundamentally irrational!

Engineering is paradigmatic of what is undervalued in Western 'high' culture, that is, in the culture of ideas, of education, of art, of morality (and of the monotheistic religions). Engineering is contingent, constrained by dictated value judgements and highly particular. Its problem solutions are context sensitive, pluralistic, subject to uncertainty, subject to change over time and action directed.

By contrast, mathematics is paradigmatic of what has been most admired in Western 'high' culture, namely reasoning that is abstract, necessary and value free; and problem solutions that are universal, certain, unique and timeless. Historically, 'demonstration', meaning mathematico-deductive argument, is the form of reasoning that the most respected Western philosophers from Plato and Aristotle to the early Wittgenstein have striven for, rejecting reasoning based on the probable, the concrete and the contingent. Reasoning 'in the geometric manner' is also the mantle in which modern science was cloaked from Descartes and Galileo through Einstein and Schrödinger. By the twentieth century, science had won growing public acceptance as the paradigmatic application of reason to experience, and thus as uniquely capable of disclosing the truth about reality. This acceptance is indebted at least in part to science's use of esoteric mathematics and

DOI 10.1179/030801804225012572

 Published by Maney for the Institute of Materials, Minerals and Mining

a hybrid experimental logic that seems deductive (but is in fact an instance of the 'fallacy of affirming the antecedent', as was noted in the seventeenth century).

The price we have paid for this identification of knowledge and truth with necessity and its cognate concepts is a radical divorce of reason from action, one manifestation of which is valuing science more highly than engineering. This divorce was already considered a fact for ancient philosophers, and it remained influential throughout the twentieth century. Aristotle argued that because action entails contingency, particularity and uncertainty, there can be no 'science' of action.[2] Knowledge/science cannot determine action because what is meant by 'knowledge'/'science' is the necessary, the universal and the certain. This creates a gulf between theory and practice that cannot be bridged by deductive reasoning, which alone is necessary and alone is able to achieve certainty. By default, then, action is ultimately wilful, and determined by desire, which is essentially irrational.

In the course of the nineteenth century, various cultural critics attacked this conception of rationality, and in the twentieth century a number of important philosophers explored contingency based interpretations of rationality. But with few exceptions, among them John Dewey, the spectacle of contemporary technological accomplishments did not suggest to these thinkers that in engineering, an effective contingency based model of rational action was being manifested. On the contrary, the development of bold new scientific theories, as well as innovations in mathematics and logic, reinforced the prejudice that necessity based rationality as exemplified by science was the key to understanding experience and disclosing reality. Engineering continued to find its place as science's handmaiden.

ENGINEERING *V.* SCIENCE

Engineering is commonly described by the scientific community as applied science, and it is accepted as such not only by the general public, but even by the engineering community and its leaders. This characterisation of engineering was built into *Science: The Endless Frontier*, the 1945 report to the President that transformed post-war US science and technology policy to global effect.[3] The report was written by Vannevar Bush, who had been an electrical engineering professor at MIT and later President of the Carnegie Institution before being made head of the Office of Scientific Research and Development (OSRD) by President Roosevelt in 1940. It was the extraordinary wartime success of OSRD that made Bush's case for reversing the historic US policy of not using public funds to support 'pure' science.

Bush was well aware that many of what were promoted as OSRD scientific triumphs, including the atomic bomb, radar and electronic countermeasure devices, mass production of penicillin and blood plasma, and the pioneer electronic computer ENIAC, were at least equally engineering triumphs. But he was also astute enough politically to appreciate the greater cultural prestige attached to science. Furthermore, as engineering was by 1945 overwhelmingly incorporated into profit driven enterprises, using public funds to support engineering related activities conflicted with the ethos of industrial capitalism. *Science: The Endless Frontier* thus presented a scenario in which public investment in 'pure' scientific research was necessary because this disinterested research, aimed only at understanding nature, alone generated the kind of knowledge that made available to engineering and industry could create engines of economic growth and anchor future national security.

Bush also was well aware that the 'real world' science–engineering–innovation process was far more complicated than this linear model represented it as being. Historically, engineering and technology had led scientific theory at least until the second half of the nineteenth century. At that time, innovations in the chemical, electrical, transportation and communication industries were systematically coupling science and engineering, motivating the creation of proprietary industrial research laboratories on the one hand and, in Germany, publicly funded research institutes on the other. But in almost every instance of innovation, from the steam engine and the telegraph to the photocopier and the computer, creative non-scientists triggered a form of positive feedback between research and innovation: commercially successful innovations stimulated new science, which enabled new engineering, which led to improved or new applications, which drove further research and newer innovations.

Bush's report was directly responsible for the creation, after bitter political controversy, of the US National Science Foundation (NSF), which rejected the very idea of engineering research right into the 1980s. The NSF position was that research meant new knowledge, and knowledge was solely the purview of science. Engineers merely applied knowledge in practical ways, which implied that any intellectually interesting issues posed by technical knowledge were in the domain of science, not engineering. Philosophy of science, for example, quickly became a respected subdiscipline of philosophy, pursued since the nineteenth century by leading philosophical and scientific thinkers. It has been complemented in the twentieth century by the rise of history of science and sociology of science as scholarly disciplines. Philosophy of engineering, by contrast, is virtually unknown in the Anglo-American world, and history and sociology of engineering are marginal subspecialities, at best.[4]

Starting in the early 1960s, academic science, technology and society (STS) programmes have had a significant effect in making large numbers of students aware of environmental, political and ethical issues associated with the social impact of *technology*.[5] But except for courses in engineering ethics, *engineering* is treated in almost all the courses that make up such programmes as a black box, as a step in the technological innovation process, or, in case studies, as technical problem solving. Engineering as it is practised in commercial or governmental contexts is rarely addressed. STS scholarship, however, has generated a vastly richer understanding of technological innovation as a complex social process. The process is one in which technical knowledge is selectively exploited on behalf of institution specific agendas driven by commercial and/or political values.[6] It is the way that engineers function as enablers of this process of selective exploitation of technical knowledge that needs to be understood in order to appreciate engineering as exemplifying a distinctive form of rationality vis à vis science.

Whatever the reasons for the low cultural esteem in which engineering is held, the consequences for society are profound.[7] Technological innovation continues to be a primary agent of social change, as it has been since the industrial revolution began in the late eighteenth century. The power of technologies, which increased at an accelerating rate throughout the twentieth century, poses increasingly serious social, political and environmental challenges. Our responses to these challenges have been woefully inadequate, reflecting a preoccupation with arguing the respective merits of competing moral, ethical, political and philosophical universal principles. Because after two thousand four hundred years, mainstream Western philosophy has still not reached a consensus on what these universal and necessary social, ethical and political values are, technology policy debates dissolve into ideological conflict.

In fact, the situation is far worse than this. Technological action is only one instance of profoundly threatening global challenges posed by economic, social, political, cultural and religious action. All forms of action directed policy debate, not just technology policy, suffer from the gulf between theory and practice, knowledge and action, that even Aristotle had identified as a consequence of embracing a necessity based conception of rationality. Understanding engineering reasoning will not resolve these problems, but it can lead us out into an examination of philosophies of the contingent and the concrete that could point the way to solutions.[8]

HOW IS ENGINEERING DISTINCTIVE?

The definition of engineering problems, as well as of what will count as acceptable solutions to them, explicitly depends on highly contingent value judgements that are external to the technical expertise engineers command. These value judgements derive from the projected economic, social and/or political consequences of the implementation of solutions to engineering problems. The assessment of these consequences in turn reflects the fact that engineering practice always takes place within highly specific, commercial and/or political action contexts. Thus engineers, in order to function as engineers, must have a boss, or at least a client.[9] Scientists, on the other hand, are perceived as disinterested pursuers of universally true knowledge of the way things are. Their problems are given by Nature, not by their employers, and Nature is the sole arbiter of correct solutions.

Typically, engineers solve problems for enterprises whose management is already committed to specific courses of action and who employ engineers to enable those courses of action. Neither the definition nor the solution of science problems, by contrast, is dependent on action – though research may be motivated and funded by an action agenda, as in the case of nuclear science in the Manhattan Project – and value judgements external to the methodology of science are prohibited from a role in defining problems or proposing solutions.

Obviously, engineers *use* mathematical and scientific knowledge to solve their problems, but they do so in ways utterly different from the ways that mathematicians and scientists solve *their* problems. Engineers use mathematical and scientific knowledge in ways that are analogous to scientists' use of mathematics and technology when solving scientific problems, namely, on their own terms. For physicists, mathematics is a source of conceptual 'tools' to be used opportunistically to solve physics problems to the satisfaction of physicists. Mathematicians may be dismayed by the way 'their' mathematics is so used and might not accept as solutions to problems in mathematics the solutions accepted by physicists to physics problems, but that is irrelevant to physicists.

A similar situation exists with regard to engineers' use of scientific theories and mathematical techniques. These serve as conceptual tools and techniques to be used opportunistically by engineers on engineering's terms. In addition, when engineers use materials from science and mathematics, the universalistic character of these materials must be adapted to the particularity of engineering problems. Engineering is thus no more applied science than physics, for example, is applied mathematics.

There is a profound difference between engineering design and scientific theorising that further undermines the characterisation of engineering as applied science. While at any point in time there may be rival scientific theories of some phenomenon, in principle there can be only one theory that is 'true', namely the uniquely correct account of the way things are 'out there'. Design, however, is an irreducibly pluralistic exercise of reason because of the role played in design by contingent value judgements, which from the perspective of working engineers often appear arbitrary. These contingent value judgements – embodied in performance specifications and specification of size, weight, production cost, reliability, materials, time to market, manufacturability, serviceability – determine the parameters in terms of which both engineering problems and what will be recognised by management as *acceptable* solutions to them are defined. Furthermore, designs are open ended: they evolve over time as problem and solution parameter weights vary.

Design is thus a contextual and a historical process as well as being intensely particular. Scientific theories, on the other hand, if correct do not evolve; ideally they are closed and unique. Where scientists aim at the truth about nature, engineering design reflects what Herbert Simon, describing managerial decisionmaking, called 'bounded rationality' and 'satisficing' – consciously operating under conditions of partial information and acting on solutions judged good enough to do the job that needs to be done, even though they are not optimal.[10]

While engineering problems are explicitly action directed and driven by value judgements, scientific theories are explicitly value neutral and their purpose understanding. The whole point of the seventeenth century methodological 'revolution' in the study of nature was elimination of the person of the subject of knowledge from the knowledge itself. This had as a corollary effect eliminating any necessary connection between knowledge so gained and action by the subject. Scientific knowledge is equivocal with regard to action. That is, what we are to *do* with scientific knowledge when achieved cannot be a question for scientific knowledge. Technology, however, is intrinsically action directed. Automobiles are for driving, while a theory of the nucleus is a theory of the nucleus, not 'for' building a bomb or a nuclear reactor or anything else for that matter, except incorporation into a wider theory.

Basing action on scientific knowledge requires supervenient value judgements, adding judgements to science that come from outside science, for example from governments and entrepreneurs. At the birth of modern science, Francis Bacon and Descartes had proclaimed that scientific knowledge would give us power over nature with which to improve the human condition, but long before the seventeenth century was over it had been recognised that scientific knowledge and improving the human condition were disjoint enterprises![11]

CONTINGENCY IN WESTERN PHILOSOPHY

Reflecting on the distinctiveness of engineering vis à vis science suggests a wider distinction within Western 'high' culture between two clusters of cognate concepts, organised here (see table overleaf) under two covering principles: the familiar principle of sufficient reason (PSR), and what I have called a principle of insufficient reason (PIR).[12] These concept clusters are neither unique, nor exclusive, nor exhaustive. They are offered here as being suggestive of two modes of reasoning, of two different conceptions of what it means to give reasons and to be reasonable, and of what will constitute knowledge and truth. The cluster of concepts listed under PSR, in which necessity seems to me to play a pivotal role, is the preferred one in mainstream Western philosophy. It is critical to what 'rationality' means in the dominant philosophical-mathematical-scientific tradition. The concepts listed under PIR, on the other hand, in which contingency plays a comparably pivotal role, are commonly associated by PSR with sophistry, rhetoric, scepticism, historicism, psychologism and relativism, all having pejorative connotations.

The Western philosophical tradition has been dominated by a necessity based model of rationality expressive of PSR that is epitomised by mathematics and exemplified in modern

Two clusters of cognate concepts: the principles of sufficient reason (PSR) and of insufficient reason (PIR)

PSR	PIR
Intellect	Will
Reality	Experience
Knowledge	Belief
Truth	Opinion
Certainty	Probability
Objectivity	Subjectivity
Universality	Particularity
Absolute	Relative
Necessary	Contingent
Deduction	Induction
Abstract	Concrete
Theory	Practice
Contemplation	Action
Understanding	Use
Prediction	Anticipation
Unique	Plural
Closed	Open ended
Timeless	Historical
Utopian	Contextual

science. What is subjugated in this tradition is a contingency based model of rationality that is expressive of PIR and exemplified in engineering. For a philosopher working with PIR concepts, knowledge, truth and certainty as defined under PSR simply do not exist. They must be redefined consistent with belief, opinion and probability if they are to refer to anything actual. For philosophers working under PSR, the concepts associated with PIR are what must be transcended in order to *achieve* knowledge, truth and certainty.

ENGINEERING AND SCIENCE: TWO RATIONALITIES?

The rationality of engineering can be described as being different from the rationality of science in exactly the same way that the rationality of contingency based philosophy is distinct from the rationality of necessity based philosophy. It is particularly significant for identifying these as two different conceptions of rationality that the fact/value distinction is central to so called 'hard' scientific reasoning but impossible for engineering reasoning; and that engineering problem solving intrinsically anticipates action, whereas scientific problem solving does not.

The contrast between the PSR and PIR concept clusters does as a matter of historical fact reflect an open 'war' between two competing conceptions of rationality in the history of Western philosophy. This war begins with Plato's attack in his *Gorgias* on the Sophists[13] as abusers of reason, teachers of tricks for winning arguments who do not know what the good, the right and the true are. They are thus not philosophers at all, not lovers of wisdom as Socrates was. But the Sophists, in the words of historian Nancy Struever, deliberately chose 'to shun the ideal sphere where pure reason and perfect justice reside', which for Plato was the objective of philosophy, 'for the shifting and uncertain field of action and discourse'.[14] The Sophists denied the reality or even the possibility of absolute truth and absolute value, denying as well the superiority of the universal to the particular and of abstract theory to concrete practice.

For the Sophists, the goal of philosophy was in the first instance illuminating action. For them, the way to philosophy was through rhetoric, which was not only techniques of persuasive speech, but the discovery *through* social speech of how to act well. Plato's desire for 'purity of thought and communication' was for the Sophists a delusion, and even the power of deductive logic to compel assent was for them (Struever again) 'mediated through the passions, not just the intellect'. Protagoras' claim, mocked by Plato,[15] that 'Man is the measure of all things' thus reflected a view of philosophy as rooted in experience, not in an unexperienced and unexperiencable 'reality' that transcended experience. As such, the goal of discovering the best way for a person to act must proceed from an understanding of how people act, of *how* Man 'measures' things, how people, individually and in groups, assign values to their experiences.

The triumph of the Platonic–Aristotelian interpretation of philosophy not only subordinated action to understanding, but was couched in terms that trivialised a concern with action as ignoble. Isocrates, a contemporary of Socrates and a student of Gorgias, argued passionately but unsuccessfully against this interpretation of philosophy on the grounds that experience is in fact contingent, particular and uncertain. Decades before Aristotle, Isocrates saw that basing philosophy on necessity, universality and certainty entailed an abstraction from experience that made such knowledge useless for action. In the *Antidosis*, Isocrates turned the already pejorative term 'sophist' against Plato. It was Plato, he said, who was the sophist, teaching intellectual gamesmanship that gave us no help in making decisions, not the rhetoricians. The rhetoricians were the true philosophers, pursuing practical wisdom.

In his *Rhetoric* and *Nicomachaean Ethics*,[16] as well as in *On the Soul*, *Posterior Analytics* and *Politics*, Aristotle acknowledged a gulf between theoretical wisdom and practical wisdom that cannot be bridged by reason. Rhetoric, he writes, is an offshoot of dialectics applied to political science and ethical studies. 'There are few facts of the necessary type that can form the basis of rhetorical syllogisms. Most of the things about which we can make decisions and into which we inquire present us with alternative possibilities. For it is about our actions that we deliberate and inquire, and all our actions have a contingent character; hardly any of them are determined by necessity.' All action based reasoning is rhetorical and as rhetoric and dialectic are practical faculties and essentially contingent, they cannot be sciences and therefore there cannot be a science of action.[17]

Rhetoric and dialectic, Aristotle noted, are the only arts of reasoning that draw opposing conclusions, in principle in order to explore vulnerabilities of probable arguments in pursuit of the 'right' conclusion.[18] Of course, this opens the possibility of abuse of rhetorical and dialectical skills if techniques of effective persuasion are separated from guiding values. Over two thousand three hundred years ago, then, what would become the core issue of twentieth century critics of technology had already been raised: that means have overwhelmed ends, that a fascination with technique has overwhelmed any understanding of why to employ technique, how to employ it and to what ends. On the Aristotelian view, engineering is allied to rhetoric, which lacks understanding and rationality but promotes action. Science possesses understanding and rationality, but is equivocal with respect to action!

That necessity and contingency were 'at war' intellectually as bases of competing conceptions of rationality is fundamental to Classical scepticism, which rests on a rejection of a necessity based conception of knowledge and of reason. In his *Academica*, written in the first century BCE, and an important influence on Renaissance thought, Cicero defended the 'cleansing' of philosophy of the concepts 'necessity' and 'certainty'. The sceptical philosophers wanted knowledge and reason defined in terms of contingency and probability because these are facts of experience. No one, they noted, has yet provided a criterion for identifying universal, necessary and certain knowledge and truth. Philosophical scepticism is thus a call for a recovery of what we mean by the terms 'knowledge' and 'reason', from the self-proclaimed 'true philosophers' who have dogmatically co-opted the right to define those terms.

Sceptical philosophy was unacceptable to Christianity – Augustine, for example, once he became a Christian considered it imperative to refute scepticism – because Christianity preaches an absolute truth. By the late medieval period, however, the primacy of necessity and universality in philosophical and theological reasoning was being challenged within Christian universities. In the fourteenth century, Duns Scotus and William of Ockham made will and particularity central to rationality. The political no less than the intellectual and theological controversies precipitated by this shift from universal to particular and from logic to will were intensified by the Renaissance revival of Cicero's writings in the fifteenth century and in the sixteenth century by the translation into Latin of Classical sceptical philosophical manuscripts.[19] The nature of rationality and its limits, the respective claims of certitude and probabilism, were critical issues for the Protestant Reformation and the Catholic Counter-Reformation as well as for Renaissance philosophy.

It was in the Renaissance that contingency made its strongest assault on necessity as the basis of philosophy and rationality. The revival by the Humanists of rhetoric and of history as the 'true' bases of philosophy precisely *because* of their focus on action and embrace of particularity and contingency was an open declaration of cultural 'war'. 'Rhetorical concepts of discourse emphasize change . . . the many . . . the particular . . . emphases which are essential in a serious commitment to historical understanding, i.e., historicism.'[20] And indeed the Humanists invented historicism, which carries with it contextualism, relativism, pluralism and openendedness.[21] Rhetoric, like engineering, is coupled to action, to decisionmaking in order to act, and to the making of distinctions in order to 'rationalise' decisionmaking. Also like engineering, rhetoric's goal is 'manmade stability in an unstable world of relationships'. Not surprisingly, the roots of modern engineering also lie in the Renaissance. The Humanists recovered, edited and published numerous Classical engineering texts, among them Vitruvius' *On Architecture*, books on mechanics by Philo of Byzantium and Hero of Alexander, and applied mathematical works by Archimedes. Concurrently, the design of more complex and more capable machinery was enabled by the invention of engineering drawing – cutaway machine drawings, 'exploded' views of parts, orthogonal projection – itself indebted to the spread among artists after 1450 of central vanishing point perspective drawing techniques. This was coupled to intensified industrial and commercial activity, leading to increasingly complex military and civilian technological projects.[22]

The Humanist assault on necessity was rebuffed, of course. It was defeated by the overwhelming success of explicitly antisceptical, necessity based seventeenth century Rationalist philosophies such as those of Descartes, Spinoza and Leibniz, by the rise of modern science and its materialist-determinist interpretation of nature, and by the eighteenth century apotheosis of Reason as the ultimate value and even the ultimate reality. Hume's attempt to formulate necessity free theories of knowledge and ethics were crushed by the necessitarian philosophies of Kant and Hegel and by the growing power of the cult of science. In the nineteenth century, however, the Romantic literary revolt against 'the Age of Reason' and 'soulless' science was complemented by critiques of necessity based philosophy in work by Schopenhauer, Kierkegaard, Nietzsche and Bergson that emphasised the primacy of will and action, not abstract reason.

From its origins in the 1870s, American pragmatism was an action centred philosophy that made contingency central to its conception of rationality and to its conceptualisation of experience. In his *Quest for Certainty*, John Dewey explicitly contrasted necessity and contingency as rival conceptions of rationality and competing bases of philosophy. Unlike the Romantics and the philosophical critics of reason, however, pragmatists generally and Dewey especially were enthusiasts for science, the scientific method and the application of scientific reasoning to all aspects of life. But for Dewey, the key to understanding science lay in engineering![23] Dewey argued that science was a form of engineering, that it was only hypothetically abstract, universal, necessary and certain. In truth science was as value laden and 'interested', hence as contextual, as engineering.

For Dewey, the hypothesised necessity based rationality of modern science was an idealisation of contingency provoked by experience. The experience of insecurity, of vulnerability, of the 'fragility of the human condition' provokes religion as one response, a philosophy that promises universal, necessary and certain truth as another, closely related response and also the response of effective, because reasoned, action. Science and engineering are thus not truly opposed to one another. There is one process in which both inhere: the process of systematic correlation of action with its actual and intended consequences. For cultural reasons, science has been misperceived as a form of necessity based philosophy, which Dewey stigmatised as religion under another name.[24]

TOWARDS A PHILOSOPHY OF ENGINEERING

What is the point of this sketch of an outline of a history of the idea of contingency in Western philosophy? What claims is this sketch intended to support?

First, that there *have* been rival conceptions of rationality from the beginning of Western philosophy, between which open hostility has been the historic norm, proponents of each routinely attacking proponents of the other as deluded, at best.

Second, that necessity and contingency have played the role of what the sociologist Alfred Schutz called 'key concepts' in these rival models of rationality, that is, concepts whose function, when clarified, simultaneously illuminates a cluster of correlated concepts.

Third, that the choice of basing rationality *either* on necessity *or* on contingency underlies mutually exclusive philosophical theories of truth, knowledge, values/action and reality.

Fourth, that engineering has strong affinities with contingency based models of rationality, that this strand of Western philosophy is the intellectual 'home' of engineering, while necessity based models of rationality with which science has strong affinities have dominated the Western tradition.

Fifth, that action poses a serious problem for the necessity based model because of a disjunction between theory and practice, while action is incorporated into the core of the contingency based model.

Finally, that philosophy is relevant to engineering; that understanding engineering fully as a practice and as a form of reasoning requires appreciating engineering's place within a particular philosophical tradition; more, that it requires recognising that engineering is an instance of a particular model of rationality that is the nexus of a cluster of cognate concepts that have implications for engineering reasoning and practice.

Engineering practice in the modern world is embedded in a very particular social context, one that has evolved out of mid twentieth century industrial capitalism. This context today is distributed globally in ways that ignore national boundaries, political philosophies and social organisation. The common denominator is the process within which engineers function. As alluded to above, this process is one in which engineering serves managerial agendas. Engineers apply their expertise to the solution of problems that derive from these (commercial or political or military) agendas, and their solutions enable the realisation of these agendas. Engineering is thus ineluctably a sociopolitical, as much as a technical knowledge, practice. As a matter of historical fact, engineers in the Anglo-American world have overwhelmingly insisted that they are only technical problem solvers, that accountability for actions based on their solutions and for consequences of those actions lies with others. This insistence rings hollow, however, with deeper insight into the nature of engineering and the cumulation of negative consequences of technological action.

If engineering reasoning is by its very nature embedded in action contexts, then engineers cannot escape sharing responsibility for that action. But it is only within the framework of an action philosophy that we can apply value judgements rationally to the action that engineering, and engineers, enable. 'Rational' technology policymaking and technology assessment inevitably elude intellectuals who come to these processes with the prejudices associated with the necessity based intellectual-philosophical tradition – for example, believing that the process requires identifying universal principles and values from which 'right' technological action and 'good' engineering can be deduced; or who believe that as this effort is hopeless, the process should take as its goal a 'functional' balance among the interested parties, whose respective interests are weighted in a way that is misleadingly, often cynically, called 'pragmatic'.

'Pragmatism' was an American philosophical innovation, initiated by Charles Sanders Peirce in the 1860s and 70s, adapted and promoted by William James at the turn of the century, but most systematically developed by John Dewey beginning in the 1890s. It is pragmatism that seems to me to hold out the greatest hope for the rational assessment of technological action and of engineering as its enabler; the greatest hope, too, for a meaningful – and implementable – engineering ethics. 'Instrumentalism' functions as a key concept in Dewey's version of pragmatism: clarifying this concept simultaneously clarifies a cluster of correlated concepts. In the necessity based/principle of sufficient reason philosophical tradition, instrumentalism is a pejorative term, implying a focus on means rather than ends, on getting some job done rather than on pursuing an understanding of what ultimately gives that job value and meaning, thereby legitimating doing that job in the first place. (After two thousand four hundred years with no consensus yet on such an understanding, philosophers attribute the highest value to the pursuit itself, a move to which Plato had recourse in order to justify Socrates' inability to identify the universal values he believed in.)

What Dewey means by instrumentalism, however, differs fundamentally from its meaning in mainstream philosophy. For Dewey it is the name of the complex process through which we respond deliberately and effectively to experience, a name for the content of consciousness. Consciousness, in turn, is the selectively interested, actively engaged, constantly evolving interactive process, ultimately intersubjective, that produces experience. Mind, as subject of experience, and world, as object of experience, are both intellectual constructs that misleadingly attribute thinghood to aspects of this process. What is real is the process, the constantly changing process, of consciousness. The self-active aspect of consciousness is reflected in the selectivity of our attention and in the projection of structure, including the structures of closure, anticipation and control, onto this continually changing, fundamentally contingent experience of self and world. More broadly, the ultimacy of process – within which we make contingent distinctions based on interests and to which we selectively attribute thinghood – is central to Dewey's philosophy. It was the basis for his opposition to all dichotomous, either/or thinking, to all abstraction from experience of 'atomic' realities that exist outside the process with fixed properties of their own. Mind attributes thinghood all the time, of course, to features of the content of experience, but what we mean by each of these 'things', by space, time, matter, energy, atom, gene, earth, universe, continually evolves as experience, and our interests, do.

The active and interested character of consciousness simultaneously creates the context of inquiry, that is, thinking focused on some facet of experience that appears as problematic and that provokes a response to resolving that problematicity. Explicating the logic of inquiry is the heart of Dewey's pragmatism and it is to that logic that instrumentalism refers. Inquiry is cognitive consciousness; it appears as a deliberate reflection on wanting to change a particular state of affairs, either to end a present undesirable one or bring about a desired but absent one.

Note that inquiry is intrinsically value laden, teleological, emotive and wilful, but also logical. What makes inquiry and cognition rational for Dewey is the clarity of the determination and assessment of the end desired, the appropriateness of the means specified to achieve that end, and the attention paid to the evolving experience of implementing the specified means, which may require modifying, even abandoning, the end no less than modifying the means. Consistent with his pragmatist framework, what we mean by 'knowledge', 'truth' and 'reality' involves beliefs keyed to the perceived effectiveness of actions, which again makes values essential to these definitions.

CONCLUSION: GETTING THERE FROM HERE

Dewey's instrumentalist conception of rationality seems to me precisely the rationality of engineering, as Dewey himself recognised. His pragmatic philosophy can be the framework for a philosophy of engineering, and a philosophy of action generally, one that does full justice to the pervasively contingent realities of engineering practice. At the same time, it can be extended beyond engineering to encompass the social process by means of which engineering knowledge, and engineers, are selectively exploited in support of commercial and political agendas that they have no hand in setting. Given the increasingly problematic character of technological action for societies literally worldwide – with more and more at stake physically, economically and culturally, and higher stakes, for more people, in more countries – more effective responses to technology related problems are demanded than the all too visible hand of corporate and entrepreneurial greed, national political agendas, religious ideology or fatalism. As we move into an era of intensified innovation and activity in a wide range of biotechnologies and nanotechnologies, even as existing environmental, energy, food, water, health, wealth distribution and demographic problems worsen, a philosophical framework within which to assess values critically is long overdue.

There is no sign that traditional philosophy can provide such a framework, but studying engineering as a functioning real world implementation of Dewey's pragmatism seems a fertile approach to a starting point for developing such a framework. Dewey, however, left a glaring hole in his theory of experience: how to evaluate ends? If experience is all there is, with no 'beyond experience' to validate what we mean by knowledge and truth, values and meanings, and if ends are simply 'there' in experience, how can we judge whether we should want what we find that we do want? How can we use the terms 'good' and 'bad' with reference to ends without falling into instrumentalism in the narrow, traditionally pejorative sense in which the rationality of means can be studied critically but not ends? How can experience be a closed and fundamentally contingent system of relationships and still be a source of all of the values and meanings required by a consistent and comprehensive philosophy of action. One approach to a solution to this problem may lie in a twentieth century intellectual development that cuts across the scientific disciplines: relationalism.

For almost two and a half millennia, reality was attributed by Western thinkers, and by Western popular culture too, to elementary things, possessing fixed properties out of which natural phenomena as experienced are composed. This finds expression in the materialistic determinism of modern science, the analytic method developed by its founders, the subject-predicate logic that dominated Western theories of reasoning from Aristotle to the nineteenth century, and atomism in its many forms. The atomic theory of matter, the cell theory in biology, the germ theory of disease, the gene theory of inheritance, social atomism, all are instances of elementary unit thinking and modelling of reality. The formulation in the last third of the nineteenth century of symbolic logics of relations and field theories of electricity and magnetism first opened the way to a reconceptualisation of reality by adding relationships to the list of the ultimately real.

The electromagnetic field is a relational structure that, though immaterial, is nevertheless a seat of forces. Durkheim conceptualised society as a network of relationships that was also a seat of forces acting on individual members of society. Saussure did the same for language, developing a theory of language as a closed system of relations. This system is itself the source of all linguistic meanings and values in spite of language being a 'social fact', hence intersubjective, and referring beyond itself, for example to the world. In Einstein's special and general theories of relativity, space and time are transformed from Newtonian thinghood into relationships, and so are mass and energy. Concurrently, David Hilbert championed interpreting mathematics as a network of logical relationships, and Vilfredo Pareto modelled the economy relationally. In mid century, the anthropologist Claude Levi-Strauss modelled cultures as relational structures, and in the 1960s and 70s structuralism became a major explanatory tool in the humanities and social sciences.

Structuralism in the humanities and social sciences echoed one of the great discoveries of nineteenth century chemistry, namely that structure itself could be a causal agent. In the case of chemistry, this discovery was connected to the spatial arrangement of atoms within a molecule. Molecules with exactly the same atomic constituents could have different properties depending on the 'stereometry' of the molecule, the way those atoms were organised. The importance of structure as a constituent of reality was rapidly assimilated by physics, sociology, linguistics, economics and anthropology. To highlight one example, X-ray crystallography, initially conceived as a way of proving that X-rays were electromagnetic waves, quickly became a tool for revealing molecular structure. Techniques for crystallising proteins enabled Linus Pauling to discover the alpha helix structure of proteins, and permitted Rosalind Franklin, *inter alia*, to generate the data necessary to validate the Watson–Crick double helix model for the structure of DNA. Very quickly it was discovered that the action of DNA was a function of the *pattern* of the four bases held in place by the outer 'shell' of phosphates and sugars. It was this pattern alone that distinguished one life form from another.

By the turn of the twenty-first century, study of the properties of structures had been enhanced by the convergence of network theory, system level modelling of phenomena, the study of self-organising, non-linear, far from equilibrium systems, and information theory. This convergence has generated new relational theories of reality. There is, for example, a growing recognition that genes and proteins act in and through extended gene, protein and gene–protein networks, not only within individual cells but also among cell networks. Cognitive neuroscience supports modelling the mind as activation patterns in neuronal–glial networks. One approach to modelling a quantum theory of gravity involves the idea that the universe itself is an information structure.[25]

Interpreting physical, biological and social realities in terms of networks is allied today to increasingly sophisticated tools for studying and modelling networks. Networks are relational structures with distinctive properties that are a function of the form of their structure. This is highly suggestive of an approach to extending Dewey's pragmatism by identifying 'objective' values within experience modelled as a dynamical, evolving, far from equilibrium relational structure. That experience is intrinsically normative is a corollary of the view that action is motivated by desire. The problem has always been on what grounds desires themselves can be judged. Historically, the dominant assumption in the West has been that something fundamentally external to experience – God, Reality, the Good – is necessary in order to provide such a ground. The pragmatist claim that a process interpretation of experience can ground values in experience itself was provocative, but only delivered a framework within which to critique means, not ends.

As engineering exemplifies a practice that successfully couples values and knowledge to 'the world', pursuing a philosophy of rational action by studying engineering practice seems a particularly promising vehicle for exploring experience as itself a source of values. Engineering surely is not uniquely qualified for this, but it has two claims on our attention. First, engineering embodies a contingency based conception of rationality as a complex *process* in which action and values are elementary features. This is an advance over any conception of rationality that sets values and action aside as not within the scope of rationality, knowledge and truth. Second, powerfully, there is a need today for rational technology policies that would enable more effective technological action. Engineering is now, and has for centuries been, ignored as a source of insight into the physical, social and cultural problems associated with technological innovation. That all approaches favoured by Western intellectuals continue to prove sterile seems to me to make a compelling case for this to change.

NOTES

1. S. L. Goldman: 'Philosophy, engineering and Western culture', in *Broad and Narrow Interpretations of Philosophy of Technology*, (ed. P. T. Durbin); 1990, Amsterdam, Kluwer.
2. Aristotle: *Rhetoric*, 1357a23–28.
3. V. Bush: *Science: The Endless Frontier*; 1980, Washington, DC, National Science Foundation Press.
4. C. Mitcham: *Thinking Through Technology: The Path Between Engineering and Philosophy*; 1999, Chicago, IL, University of Chicago Press.
5. S. H. Cutcliffe: *Ideas, Machines, and Values: An Introduction to Science, Technology, and Society Studies*; 2000, Lanham, MD, Rowman and Littlefield.
6. S. L. Goldman: 'The social captivity of engineering', in *Critical Perspectives on Non-Academic Science and Engineering*, (ed. P. T. Durbin); 1991, Bethlehem, PA, Lehigh University Press.

7. S. L. Goldman: 'Images of science and technology in popular films', *Science, Technology and Human Values*, 1989, **14**, 275–301.
8. S. L. Goldman: 'No innovation without representation: technological action in a democratic society', in *New Worlds, New Ideas, New Issues*, (ed. S. H. Cutcliffe *et al.*); 1992, Bethlehem, PA, Lehigh University Press.
9. S. L. Goldman: 'The social captivity of engineering' (see Note 6).
10. H. A. Simon: *Models of Bounded Rationality*, Vol. 3; 1997, Cambridge, MA, MIT Press.
11. C. Webster: *The Great Instauration: Science, Medicine and Reform 1626–1660*; 1976, New York, NY, Holmes and Meier.
12. S. L. Goldman: 'Philosophy, engineering and Western culture' (see Note 1).
13. But see M. Untersteiner: *The Sophists*; 1954, New York, NY, Philosophical Library.
14. N. Struever: *The Language of History in the Renaissance*, 10; 1960, Princeton, NJ, Princeton University Press.
15. Plato: *Cratylus*, 386A–386E.
16. Aristotle: *Nicomachaean Ethics*, books 6 and 10.
17. Aristotle: *Rhetoric*, 1357a23–28, 1359b12.
18. Aristotle: *Rhetoric*, 1355a34.
19. R. Popkin: *A History of Scepticism from Erasmus to Spinoza*; 1986, Berkeley, CA, University of California Press; C. Schmitt: *Cicero Scepticus: A Study of the Influence of the Academica in the Renaissance*; 1972, Hague, Martinus Nijhoff.
20. N. Struever: *The Language of History in the Renaissance*, p. 37 (see Note 12).
21. D. Kelley: *Foundations of Modern Historical Scholarship*; 1970, New York, NY, Columbia University Press.
22. S. Y. Edgerton: *The Heritage of Giotto's Geometry: Art and Science on the Eve of the Scientific Revolution*; 1991, Ithaca, NY, Cornell University Press.
23. J. Dewey: *The Quest for Certainty*, 84; 1960, New York, NY, Capricorn Books.
24. J. Dewey: *The Quest for Certainty*, p. 3, also 8 (see Note 20).
25. L. Smolin: *Three Roads to Quantum Gravity*; 2003, New York, NY, Basic Books.

Steven L. Goldman (slg2@lehigh.edu) is Andrew W. Mellon Distinguished Professor in the Humanities at Lehigh University, where he holds a joint appointment in the departments of philosophy and history. His teaching and research centre on the history and philosophy of modern science and technology, and on the social dynamics of contemporary technological innovation. He was for eleven years Director of Lehigh's Science, Technology and Society programme. Among a wide range of publications, he has authored or coauthored influential technology policy reports for the US government, and four books on the implications of innovation for strategic management. Since the mid 1980s he has been studying the role of engineering in technological innovation.
