Economics and Engineering: A Foreword

David Blockley

Throughout history we humans have dreamed and *purposefully* and *ingeniously* turned new ideas, and new ways of doing things, into reality based on their *worth*. I use the word *ingeniously* to mean being inventive, resourceful, and skillful. I use the word *worth* to convey more than a monetary amount, that is, all aspects of quality as fitness for purpose such as functionality, safety, resilience, and sustainability as well as economic value for money, and working within budgets.

It is my contention that knowing and doing have become artificially separated in Western intellectual culture. The emphasis on scientific knowing has led to an overconfidence in our ability to predict the future and a neglect of the need to control complex and often unforeseen, unintended consequences of our practical actions.

It is my purpose here to explore the relationship between economics and engineering not in analogy but in actuality. The strategy is, first, to set the context for this discussion; second, to look at the nature of science and mathematics in relation to engineering; and third, to explore some of what I see as the main similarities and differences between engineering and economics.

Preliminaries

Uncertainty is pervasive in the world, and it introduces a significant distinction between the scientific knowledge produced in and outside the laboratory. In classical physics we have controlled uncertainty through the precise conditions of laboratory testing. As we move outside the laboratory

History of Political Economy 52 (annual suppl.) DOI 10.1215/00182702-8717886

(world outside the laboratory, or WOL), we have to relax our grip on uncertainty. Here the uncertainty has a greater and variable impact on our ability to predict the more complex phenomena.

Engineering has largely been ignored by philosophers or subsumed under science (Mitcham 1999; Goldman 2004) because, Goldman argues, engineering employs contingency-based reasoning, in contrast to the necessity-based modeling of rationality that has dominated Western philosophy since Plato. Engineering is not just something-to-do-with-engines. To engineer is to solve problems as only we humans can.

Before the Renaissance, the same person might be an artist, artisan, architect, craftsman, mason, or engineer depending on the job he was doing—the distinctions we make nowadays were small. After the Renaissance, engineering disciplines fragmented (civil; construction; mechanical, railways and cars; electrical, power and electronics; aerospace; and computer science and software), as opportunities arose largely through the evolution of specialist scientific knowledge. Today, the engineers' professional duty of care for the safety and well-being of others requires them to examine the scope and dependability of all kinds of information, including science. However, there has been very little reflection on the way that knowledge is used and the "fit" between engineering and other disciplines. History, philosophy, economics, and politics have only a nominal role in the education of engineers. While almost all engineering societies have attempted to define the nature of engineering (e.g., Royal Academy of Engineering 2019), there is little in-depth critical discussion of the role of engineers in society. As a result, there is a plethora of different views about the nature of engineering.

Engineering is not a science: whereas the purpose of science is to understand, the purpose of engineering is to act and do something practical—usually but not always to create something physical—to meet a human need or want as expressed usually by a client (Blockley 2010). The physical results of engineering work are highly testable. Indeed, Mother Nature is the final arbiter. She is the most severe taskmaster—she will find any weak points. If a computer program has a bug, then at some point it will fail, although that failure has consequences in physical reality only when the software is used, for example, to control the flight of an airplane or to decide the proportions of a bridge structure.

The Nature of Engineering

At the core there are four stages to engineering tasks: design, make, operate, and maintain. Through fragmentation between the different branches of engineering, these stages are handled differently in different disciplines. However, for the present purpose, we can divide them into two groups. The first are the "one-off" big engineering projects such as building a large dam or skyscraper. The second are the "mass-produced" projects such as computers and cell phones. In between are "small-quantity" production projects such as ships and airplanes, which show features of both. The essential difference between the two groups is the level of prototype testing that can be done before production. Mass-produced goods are extensively tested before being put into production, and heavy investment is made in factory production processes. By contrast, "one-off" products have to be "right the first time." So safety factors and conservative assumptions are necessarily greater in one-off industries, whereas margins are tighter in mass production.

The first stage of designing is turning a client brief into a clear purpose, and then coming up with possible solutions and criteria for choice between them. The criteria depend crucially on interactions between all stakeholders. Necessary criteria concern functional reliability, safety, and budgetary constraints. More recently, sustainability has become important together with resilience and robustness. Designing includes prototype testing for manufactured products but not for "one-off" products, although laboratory tests will be done for aspects of large projects (such as testing a physical model of a long span bridge in a wind tunnel).

Making, the second stage, is manufacture, construction, or building, usually performed in a factory or on-site with the participation of multiple contracting businesses in a supply chain. Operating and maintaining are given various levels of attention or inattention depending on the product. For example, software products get regular updates, whereas potholes in highways may go neglected for years due to political budget austerities. High-reliability systems like airplanes have sophisticated avionic control and maintenance systems. Feedback and feedforward from sensor data are used directly to help make decisions—sometimes automatically as in aircraft landing control systems.

Models

The relationship between engineering and science is reciprocal. As we do more (engineer), then we know more (science), and hence we can do more and know more in an ever upward spiral. At the heart of scientific knowing are models. The word *model* is important and controversial when used to describe scientific theory (Cartwright 1999). However, the idea of a model is particularly important in engineering. Nevertheless, there is no settled view as to the nature of what constitutes a model.

For the reasons given earlier, engineers only think intuitively about the models they use. Most engineers know that the science they use is incomplete and approximations are required. They typically require models to (a) work and (b) be tractable. The first is checked by experiment in laboratory conditions, but perhaps more important by practical use. Experience builds by trial and error. The tractability of theory has changed dramatically over the years chiefly through advances in mathematical techniques and computing. Almost universally, engineers see mathematics purely as a tool. Many practitioners are wary of what they see as "overly" complicated mathematical analysis and fight shy of adopting it. Researchers and academics are often frustrated by these attitudes. However, nowadays almost all calculations are done by computer, and therein lie some new risks. Many "pure" mathematicians find engineering methods to be ad hoc. The reason is that engineers have to approximate in order to get to solutions, and it is in these approximations that the new risks lie. The approximations are different in different applications but depend almost entirely on judgments about the uncertainties lying in approximations and other contextual assumptions.

Managing Uncertainty

Uncertainty is analyzed and judged largely in two ways, pragmatically and theoretically. The first is through experience in practice and the trial and error of what has worked in the past with "built-in" simple safety factors. The second is through research techniques. These find little application in anything other than high-risk industries like nuclear and aerospace. One-off industries rely on various kinds of simple safety factors where parametric quantities are increased or reduced appropriately to make any assumptions conservative or safe. Systems are designed wherever possible to be "fail-safe," that is, to minimize consequences should failure occur. Defense in depth is used where safety is highly critical. Here many levels of protection are designed-in, so if one fails, the next takes over. Industries that require very high reliabilities and safety levels (e.g., aerospace and nuclear) are funding research into probabilistic methods taken rather uncritically from mathematicians. However, their use in practice is still controversial because of the intuitive feelings of experienced engineers that the methods are inadequate to deal with the vagaries of operations.

Engineers face three types of uncertainty in their models. First, *random* variations in parameters (e.g., variations in the weights of people in a building). These can legitimately be modeled by mathematical theories of probability and statistics (Blockley 1980). Second, *system* uncertainties stem from the physical context in which a tested theoretical model (to a degree in the laboratory or through the experience of practical usage) is used. These are very variable in quite different contexts and hence difficult to pin down. Some *systemic* differences are deliberately introduced to make a problem tractable (e.g., engineers model the load on the floor of a building as uniformly distributed when clearly it is not—but the model is fail-safe). Likewise, systems can be modeled at varying levels of definition and abstraction to account for emergent properties where the behavior of the whole is more than the sum of the parts. Applications of probability theory, using random error terms to account for systemic differences, have proved, in my view, inadequate (Blockley 1992). Third, uncertainties in *human* and social systems that are even more difficult to control because of the tendencies for people to do the unexpected and to make mistakes (overweight vehicles crossing a bridge or a design calculation mistake). It is rare for engineers to scan for unintended consequences or to do a systematic scan for unknown unknowns. They are usually guided by previous practices that have worked and by legal guides such as regulations and codes of practice.

Engineers create models for a specific purpose, and what really matters is the quality of the model to deliver that purpose. Engineers succeed because when they have to approximate, they make assumptions that are "fail-safe," that is, always erring on the safe side when in doubt to make sure they stay in context. The dependability of models varies across engineering disciplines. For large "one-off" projects, theories are laboratory tested, but in the WOL great reliance is placed on previous practice, experience, and national regulations. For manufactured large-volume "mass-production" products, prototypes are extensively tested both in the laboratory and then in a simulated reality before being put on sale.

Attributes and Criteria—How Do We Recognize Success?

If engineering is about delivering a purpose, then how do we know if and when that purpose is achieved? Strictly and rigorously, quality is "fitness for purpose," which does not mean only functionality. Quality should cover all attributes of purpose as safety and economy. In the past, engineers have understandably focused on functionality and safety because they are necessary (but not a sufficient condition) for practical success. For example, a building must stand firm against the elements and whatever the people interacting with it require of it. While buildings in a nonseismic zone are not normally designed to withstand earthquakes, it is a legal requirement that buildings in California are designed to do so, which does not ensure that all buildings are safe, as past events have shown.

Since the Renaissance, some other aspects of quality have been diverted into other professions, for example, aesthetics to architects, accounting to quantity surveyors, and management to project managers. The result has been even more fragmentation of the professions. Only in the recent past are we collectively beginning to realize (largely through some high-profile failures) that some important requirements such as robustness, lack of vulnerability and fragility (low-probability but high-consequence events), sustainability, and resilience have “fallen through the cracks” between the professions. Hence there are new calls to emphasize whole systems engineering approaches to improve performance—particularly cost and time overruns on big projects (Blockley and Godfrey 2017). These developments are patchy and controversial among engineers. Some dismiss systems thinking as “management speak,” hence unworthy of consideration, against the views of the Royal Academy of Engineering (2007).

How Are Economics and Engineering Similar and How Are They Different?

The similarities between economics and engineering seem profound. J. F. Hayford (1917: 59) noted this when he wrote, “Economics and engineering are closely related. Economics has been defined as the social science of earning a living. With the same appropriateness engineering may be defined to be physical science applied to helping groups of men to make a better living.” The main sources of similarities and differences that I shall explore are (a) the understanding and importance of context, the dependability of the underlying models and the role of mathematics, and (b) the role of failure.

Context, Testability, and Models

To explore the importance of context, it is worth pausing to consider how the philosopher Karl Popper (1978) explained the way we perceive, sense, and share our reality. He said that we effectively inhabit three worlds. World 1 is reality, the actual physical world of which we are a part. Next, he said that we can make sense of world 1 only through world 2, our own subjective world of mind. World 2 is where we think about the things that we cannot share with anyone else. Finally, he said that we also try to make sense of world 1 (and world 2) through world 3, the world of our shared experiences, the world of objective data. Tests on engineered physical systems are devised in world 3 and are repeatable in world 1—precisely in the laboratory and more or less imprecisely in the WOL.

The simple linear deterministic supply and demand model of econometrics, such as $S = a + bP$, where S is supply and P is price, is informative but not as dependable as the way engineers use an equivalent formula such as $S = a/b$, where S is a safe breaking stress for a piece of steel, a is a tensile force, and b is a cross-sectional area of that piece of steel. The engineering relationship is accurate in the context of small forces up to an "elastic limit" for steel, though not for many other materials such as concrete. Nevertheless, engineers can use the linear elastic relationship to make fail-safe assumptions to work in the WOL, making calculations tractable even for concrete (a material with nonlinear properties). The econometric linear relationship between supply and demand is a statistical "fit" based on a regression with a great deal of inherent uncertainty and many potentially omitted variables because they are difficult to include. This model is therefore a very limited representation, but useful in understanding what is going on and what decisions need to be made to achieve purpose. Consequently, the relationship between the results and behaviors in practice is much more tenuous.

The Role of Failure

I have spent a lifetime of research looking at why engineering systems fail. The gaps between what we know, what we do, and why things go wrong are huge. The old adage "failure is an opportunity to learn" is often quoted but, in my experience, seldom appreciated sufficiently by practitioners. It has deep roots and far-reaching implications for the joining-up of theory and practice. In 1978 the sociologist Barry Turner showed that the preconditions to major disasters can incubate or develop in a way that it may be possible in some instances to identify before a final disastrous event. He pointed out that we need to develop methods for identifying those preconditions with sufficient dependability to enable decision-makers to make such politically difficult and potentially expensive decisions to avoid the even greater costs and consequences of a disaster. In subsequent research he and I and the psychologist Nick Pidgeon followed up this idea (Blockley 1992) but without much impact on practice, since the methods needed are not straightforward.

The same issues are alive in economics. For example, after the financial collapse of 2008 the queen of England, Elizabeth II, asked of the experts, "If these things were so large, how come everyone missed them?" In reply Tim Besley and Peter Hennessy (2009: 10) wrote, "The failure to foresee the timing, extent and severity of the crisis and to head it off, while it had many causes, was principally a failure of the collective imagination of many bright people." That such an event should "never happen again" is widespread across all systems, from criminal justice and social care to economics and engineering.

In my view, a systems-thinking approach is the only way to follow through Besley and Hennessy's conclusions—we have to find ways to integrate the professions. The historical fragmentation of specialisms has been spectacularly successful but has led to an inability to see the "big picture." To deal with the surprises, unexpected events, unknown unknowns of a future of climate change, uncertain politics, religious strife, and pandemics we need systems that are resilient and sustainable. This can only happen if the professions work together to "join-up" their thinking, decision-making, and actions.

References

Besley, T., and P. Hennessy. 2009. "The Global Financial Crisis—Why Didn't Anybody Notice?" *British Academy Review* 14 (November). www.thebritishacademy.ac.uk/sites/default/files/03-–Besley.pdf.

Blockley, D. 1980. *The Nature of Structural Design and Safety*. Chichester, UK: Ellis Horwood.

Blockley, D., ed. 1992. *Engineering Safety*. London: McGraw-Hill.

Blockley, D. 2010. *Engineering: A Very Short Introduction*. Oxford: Oxford University Press.

Blockley, D., and P. S. Godfrey. 2017. *Doing It Differently: Systems for Rethinking Infrastructure*. 2nd ed. London: ICE Publishing.

Cartwright, N. 1999. *The Dappled World: A Study of the Boundaries of Science*. Cambridge: Cambridge University Press.

Goldman, S. L. 2004. "Why We Need a Philosophy of Engineering: A Work in Progress." *Interdisciplinary Science Reviews* 29, no. 2: 163–76.

Hayford, J. F. 1917. "The Relation of Engineering to Economics." *Journal of Political Economy* 25, no. 1: 59–63.

Mitcham, C. 1999. *Thinking through Technology: The Path between Engineering and Philosophy*. Chicago: University of Chicago Press.

Popper, K. 1978. *Three Worlds: The Tanner Lecture on Human Values*. University of Michigan. tannerlectures.utah.edu/_documents/a-to-z/p/popper80.pdf.

Royal Academy of Engineering. 2007. *Creating Systems That Work: Principles of Engineering Systems for the Twenty-First Century*. www.raeng.org.uk/publications/reports/rae-systems-report.

Royal Academy of Engineering. 2019. "What Is Engineering?" www.raeng.org.uk/education/what-is-engineering.

Turner, B. A. 1978. *Man-Made Disasters*. London: Wykeham.