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Critical rationalism and engineering: ontology

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Abstract Engineering is often said to be 'scientific', but the nature of knowledge in engineering is different to science. Engineering has a different ontological basis—its theories address different entities and are judged by different criteria. In this paper I use Popper's three worlds ontological framework to propose a model of engineering theories, and provide an abstract logical view of engineering theories analogous to the deductive-nomological view of scientific theories. These models frame three key elements from definitions of engineering: requirements, designs of artefacts, and theories for reasoning about how artefacts will meet requirements. In a subsequent paper I use this ontological basis to explore methodological issues in the growth of engineering knowledge from the perspective of critical rationalism.

Keywords Engineering · Ontology · Critical rationalism

1 Introduction

Engineering has many philosophically interesting problems, but has only recently begun to attract attention within philosophy. As discussed by van de Poel (2010), the philosophy of engineering (as distinguished from the philosophy of technology) has until recently been largely unexplored, except as regards ethical questions in engineering. Houkes (2006, 2009) similarly argues that epistemological issues concerning the function of technological artefacts have not been well studied, but should be. Engineering, like science, is based

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on rational reasoning about the physical world. Indeed, engineering is sometimes presented as being 'scientific'. Engineers do often use or adapt scientific theories, but as will be discussed, engineering is not the same as science or applied science. The epistemological problems in engineering are similar, but different, to those in science.

This paper proposes an ontological basis for objective knowledge in engineering. I use Popper's (1977) *three worlds* ontological framework to explain how engineers reason that artefacts satisfy requirements. Aligned with this I present an abstract logical view of engineering theories, similar to the deductive-nomological view of scientific theories. This ontological basis is used in a subsequent paper, to explore methodological issues in engineering: falsification of engineering theories, and the growth of knowledge in engineering.

2 What is Engineering?

Defining 'engineering' may be at least as hard as defining 'science'. Pawley (2009) found in interviews with engineering faculty members that there is no commonly-agreed definition of engineering. Mitcham and Schatzberg (2009) give an etymological history of 'engineering', but leave its definition open. A naïve view may be that engineers just design and build artefacts. However, Davis (2010) contrasts engineering with architecture, and concludes that engineering cannot be defined simply as designing or construction. Architects design and builders build, but neither are taken to be engineers. Conversely, Davis observes that engineers also perform other kinds of activities as an essential part of their professional duties, such as inspecting designs and artefacts, or writing regulations.

Vincenti (1990, p. 6) adapts a definition by Rogers (1983) as follows: "engineering refers to the practice of organising the design and construction [and, I would add, operation] of any artifice which transforms the physical world around us to meet some recognised need." This shares elements with a definition from the profession (ECPD 1947):

> The creative application of scientific principles to design or develop structures, machines, apparatus, or manufacturing processes, or works utilising them singly or in combination; or to construct or operate the same with full cognizance of their design; or to forecast their behaviour under specific operating conditions; all as respects an intended function, economics of operation and safety to life and property.

There are three recurring elements in definitions of engineering: artefacts (here "structures, machines, apparatus, or manufacturing processes..."), requirements (here "an intended function, economics of operation and safety to life and property"), and theories (here "forecast their behaviour"). These three elements (making things, solving problems, and using theories) were also identified in Pawley's (2009) survey. Davis (1996) takes a quite different approach and argues that engineering should be defined historically as an occupation (with knowledge transmitted through a shared curriculum), and ethically as a profession. Nonetheless, Davis acknowledges that more typical definitions like those above share these three important elements. I do not settle on one definition of engineering, and avoid discussion of engineering as a profession. Instead I limit my discussion to epistemological issues within engineering, and frame the three elements: physical artefacts; requirements for these artefacts; and engineering theories for predicting whether artefacts will satisfy requirements.

Artefacts are central to engineering. There is some debate about what artefacts are. I use the term 'artefacts' for configurations of matter and energy used for some purpose. This can include structures, devices, system components, systems, and physical processes. Polanyi (1958, p. 175) similarly identifies materials, tools, and processes as the "observable things which can be defined by their participation in practical performances". (I would add fields and forces.) In engineering, artefacts are evaluated with respect to requirements, and are often designed to meet these requirements, but not necessarily so. Engineers sometimes re-purpose technology, using old inventions to meet new requirements, and sometimes use objects created by natural processes. For example mining engineers use naturally-occurring rock formations to extract mineral ores, and nuclear engineers may use freshwater streams to cool reactions in a nuclear power plant. Here I regard something as an artefact if and only if it is used (or planned to be used) in an appropriate way to physically perform a function ascribed to be within the capacity of the object. This definition is essentially the same as the 'useful-material' conception of artefacts of Houkes and Vermaas (2009). They reject this definition of 'artefact' because it does not distinguish natural from human-made objects. However my goal is not to distinguish natural from human-made things, but instead to understand how engineers work with the material world to fulfil purposes.

Although *designs* for artefacts are man-made can be physically represented on paper, I exclude them as artefacts because the importance of a design is its objective content rather than its physical representation. A design is not what ultimately satisfies requirements; instead it is the real artefact corresponding to the design which can satisfy requirements.

Software is sometimes taken to be an artefact (Goldberg and McCarthy 2008). However, is software mathematical, or a physical thing? This deserves more analysis than is possible here, but the key point is as follows. Like the design of an artefact, it it the objective content of a computer program that is important to its characterisation and identity. The objective content of a program remains unchanged, regardless of whether it is represented as magnetic regions on a hard disk, or as ink on a page. Popper (1978) also holds this view on computer programs. Nevertheless, the controversy and lessons (MacKenzie 2001) from Fetzer's (1988) paper on program verification remind us that the execution of a program on a physical computer is categorically different to the content of the program, and different to a characterisation of the program's possible behaviour using formal theories. The execution of a program on a computer system is a phenomena in the real world, and it is this phenomena which might change the world in a way that satisfies requirements. Theories of program analysis or ‘formal verification’ are not purely mathematical—they are ultimately also empirical engineering theories when they support claims that the behavior of real programmed computer systems meet requirements.

3 Characteristics of Engineering Theories

I define ‘empirical theories’ as explicit falsifiable claims used to predict and analyse phenomena. A scientific theory is an empirical theory with characteristics that may include ontologically corresponding to the world, being as universal and as simple as possible, and being explanatory. Rapp (1981) claims that basic research in engineering sciences and natural sciences share the use of empirical method, and the formulation of theories in mathematical terms. However, mathematical theories that are not claims about the physical world are not empirical theories. Pure mathematics only solves problems with respect to a formal axiomatic basis. The claim that a mathematical theory describes the physical world would make it also an empirical theory. Some empirical theories are represented in non-mathematical ways. Visual diagrams are common in sciences such as chemistry, mechanics, and optics. In engineering, Ferguson (1992) describes the long history of visual diagrams to represent designs. The function of diagrams in science and engineering is to express claims about the structure or behavior of the world; they can be falsified by them or their consequences failing to correspond to the world, and so are empirical theories.

I define ‘engineering theories’ as empirical theories used to reason about the performance of artefacts with respect to requirements. To reason about artefacts and requirements, artefacts’ designs and requirements’ specifications must be explicitly defined as objective content. Designs (and specifications) are neither commands nor propositions. They are terms that can be used in commands (“Create an artifact like this design!”) and propositions (“That artefact is like this design.”). Designs can be used prescriptively (e.g., as instructions to create a new artefact) or descriptively (e.g., to characterise a mine site before blasting, or to reverse engineer a competitor’s product). Engineering theories include adaptations of scientific theories, and empirically-validated mathematically-represented theories specifically developed within engineering research. However, engineering theories also include rules of thumb, laws of similitude underlying physical models (Vincenti 1990), tables of performance data intended to be suitable for interpolation over a limited range of a few variables, or factors of safety that emerge from engineering practice (Clausen and Cantwell 2007). Some previous authors have struggled to call some of these instruments ‘theories’—I discuss Koen’s (1988) objections below in section 6.

Below I discuss characteristics of engineering theories that have epistemological ramifications. These characteristics also distinguish engineering from science, as discussed in section 4.

3.1 Sufficient to be Phenomenological

Scientists aim to create fundamental theories that correspond ontologically and behaviourally to the world, and that explain and predict underlying relationships between phenomena. Scientific investigation in a new field can start with the collection of data tables about phenomena. However, such tables are acceptable in science only as the starting point for the development as a more general, more precise, and more explanatory theory.

Engineers might prefer such theories, but are often satisfied with theories that merely predict phenomena, even if they have no explanatory power or ontological correspondence with the world. Consider the data tables of aerodynamic performance of wing-sections, discussed by Vincenti (1990). These do not explain how air flows over wing sections, nor why one wing section performs better than another. They are only phenomenological. Nonetheless, they are the result of systematic empirical studies, support predictions about the performance of wing sections, and informed the design of early aeroplanes.

If and when deeper and better theories (from science or engineering) later become available then engineering practice may evolve to use them instead. Nonetheless, limited phenomenological theories can sometimes remain sufficient within engineering. If data tables or rules of thumb are sufficiently general, precise and accurate for engineering purposes, then there may be no need to replace them with a more ‘scientific’ theory. Vincenti (1990, p. 193) argues that sometimes science is never called on to provide an explanatory theory for designs, and provides as an example the engineering development of knowledge of flush riveting in aeronautics. Although the process to generate this knowledge was analytical, empirically-grounded, and made occasional use of mathematical equations, this phenomenological body of theory matured without the specific use of explanatory scientific theories.

3.2 Wide Variety of Levels of Precision

Engineering theories can be very precise, but many are conservative approximations. An approximate theory can be severely tested against its defined range of allowable performance. The weaker claims of less precise theories can sometimes work as a trade-off to increase confidence in the accuracy (validity) of those claims. Petrowski (1996, p. 63) says “Because engineers know that theoretical calculations and predictions can seldom capture all the variability in detail that exists in reality, they are not expected to be perfect. The way engineers have long used design formulas derived from analysis is to apply them conservatively in order to take into account a multitude of uncertainties.” An example are safety factors for the performance of an artefact. (Clausen and Cantwell 2007) The use of safety factor rules may lead to suboptimal design decisions. However, drawing on Simon’s (1969) concept of ‘satisficing’, Clausen and Cantwell discuss how these decisions may be ‘good enough’.

Laymon (1989) discusses the role of idealisation in engineering, and observes that scientists also simplify their descriptions of phenomena. Nonetheless, in science the challenge is to push theories to the limits of their precision, and to understand at this limit whether falsification is due to a fundamentally false theory, calculational mistakes, or experimental error. In contrast, theories in engineering only need to be precise enough for the theory to be used (reliably enough) to analyse some class of designs with respect to requirements.

3.3 Wide Variety in Limitations on Scope

Engineering theories can have a wide scope of applicability, but are often highly limited. Their scope can be limited to specific environmental conditions, to a specific class of designs for artefacts, or to making predictions about specific kinds of behaviors. The data tables of wing-sections discussed by Vincenti (1990) again provide an example from industrial practice. These were not a general theory of air flow over any surface, but instead allowed engineers to predict the performance of wing-sections only within a narrow range of shapes and wind-speeds. Other examples are discussed by Cuevas-Badallo (2005), who examines Hooke's Law and its limitations in only applying to some materials, and only within a limited range of stress (the *elastic range*) of those materials.

Engineering theories can be more constrained than they need to be. That is, it would often be possible to validly broaden the conditions under which they are applicable. However, if an engineering theory's conditions are part of or derive operating conditions that are acceptable for the use of an artefact, then this can be satisfactory for engineering purposes.

Limitations on the scope of engineering theories can arise from their derivation as 'special cases', where assumptions about environmental conditions or designs are factored into general theories. This may be done to improve the instrumental properties of the theory, such as its cost or ease of use. Limitations on scope can also result from the research method used. An example is parameter variation. (Vincenti 1990) The method determines the performance of artefacts across a parametrically-defined space of designs, and the scope of the resulting theory is limited to artefacts within that constrained design space. A theory with narrower scope can also be easier to validate empirically.

3.4 Wide Variety of Target Qualities

Science has traditionally studied pure physical phenomena: space, time, matter, or energy. Modern sciences study a broader range of phenomena, including for example the psychological study of subjective sensations, or the behaviours of ecological systems. Engineering analyses can include all of these phenomena, but de Vries (2010) notes that engineering theories also consider an even broader variety of socio-technical qualities that are not part of science. These include the cost to design, build and operate an artefact, the time required to design and build an artefact, the level of safety in the operation of an artefact, and the usability of an artefact in operation. Engineering requirements can constrain all of these qualities. Advances in engineering knowledge for the design, analysis, construction and operation of artefacts can be made to improve artefacts against criteria on these dimensions. Engineering design requires trade-offs to be made in performance between these physical and socio-technical qualities.

3.5 Wide Variety of Instrumental Properties

Engineering theories have *instrumental properties*, which can include the level of expertise required to effectively use the theory, the time or cost required to perform calculations using the theory, or the level of detailed design information required by the theory. Popper (1972, p. 95) thought that concerns about the difficulty of understanding and using theories were not worth pursuing. For science, there are opposing views. McMullin (1985) claims that throughout history, scientists have created simplified descriptions of the world (‘Galilean idealisation’), in order to make practically feasible the analysis of complex real world problems. Weisberg (2007) argues that Galilean idealisation is progressively abandoned by scientists as increasingly powerful analytical techniques are developed, letting them work effectively with more complex and accurate models.

Whether or not the difficulty of understanding and using theories is important in science, it is certainly an important consideration in engineering. Vincenti (1990, p. 132) discusses that analytical tools within engineering must be inexpensive and fast enough to apply, and must also be able to be used reliably, without calculation errors. Simon (1969, pp. 124–125) also notes that designers work with limited mental and physical resources in creating their designs, and applies his notion of bounded rationality to the process of design. Trade-offs in choosing between candidate designs for an artefact usually include cost considerations, but this involves not just the costs of materials and construction of the artefact, but also the costs of using engineering theories to analyse the candidate designs.

3.6 Multiple Overlapping Theories

Scientists within a field tend to hold only one theory, or consider a few competing alternative theories with the widest possible scope and most extreme precision. In engineering, there may be many as-yet-unfalsified theories with different levels of precision, different scopes of applicability (applying to different classes of designs, or ranges of operating conditions), or different instrumental properties in how easily or quickly they are able to be used.

Because of this, the forefront of engineering knowledge in a domain is not necessarily a single theory, but can instead be a set of multiple overlapping theories, each of which is the ‘best’ in terms of one or a combination of these characteristics. Trade-offs can be made in the selection of theories. So, an engineering theory need not be rejected entirely unless it fails to correspond with reality or is dominated by another theory across the range of these characteristics. For example, an engineering rule of thumb may have a very narrow scope of application and coarse level of precision compared to every other alternative theory, but be retained within the engineering body of knowledge because it is the most inexpensive and quick to use.

Arguably science, too, can work in a similar way. Levins (1966) discusses trade-offs in biological science in the creation and use of scientific models, with particular regard to trading generality for realism and precision. Weisberg (2007) builds a broader ‘Levinsonian’ concept of model idealisation in science. Incompatible scientific models might be retained because each has explanatory power within a narrow domain, or because together they have greater predictive power. Nevertheless, in science, *ceteris paribus*, it is a sufficient basis for theoretical development to replace overlapping theories by a more general one. This contrasts with engineering, where holding onto an unfalsified theory is only undesirable if it is dominated by other engineering theories across the complete range of useful criteria.

4 Countering Misconceptions about Engineering

There are many common misconceptions about engineering, which include that it is science, applied science, trial-and-error, mechanical application of knowledge, or technology. Here I briefly review some of the arguments against these misconceptions. This section helps to justify that the philosophy of engineering is not vacuous nor subsumed by the philosophy of science.

4.1 Engineering is a Science?

Engineering is often taken to be ‘scientific’, e.g. as seen in section 1. Bunge (1966) discussed the application of scientific method to technology, and equated technology with applied science (see section 4.2). Boon (2011, p. 66) holds more strongly that ‘engineering sciences’ and natural sciences “. . . cannot be fundamentally distinguished in the sense of having fundamentally different epistemic aims and methodologies.” However, here I argue instead that engineering research is only similar to science, and is not part of science.

When contrasting engineering with science, we could consider various senses of ‘engineering’: practice, research (including research method), the discipline overall, or the profession or occupation. Of these, engineering research is the closest to science, so unless otherwise specified, we can conservatively read that for ‘engineering’ here. Nonetheless, I argue in the subsequent paper (on methodology) that there are not sharp lines between engineering practice and engineering research.

Engineers Use Theories and Methods Not Acceptable in Science Engineers may use or adapt scientific theories, but also use other theories that would not be acceptable within science. As discussed above in section 3, engineering theories can be phenomenological, be highly approximate, and have a highly limited scope. In contrast, scientists aim to create theories that are fundamental or explanatory, are as precise as possible, and are as universal as possible. Engineering methods can also be unacceptable within science. Parameter variation is systematic, replicable and empirical, but is not scientific because it only leads to phenomenological theories with a highly limited scope.

Engineering Targets Requirements Whereas Science Does Not There is a teleological difference between science and engineering. Simplistically: science tries to understand the world, whereas engineering tries to change it. Simon (1969, pp. 4–5) says science "has found a way to exclude the normative and to concern itself solely with how things are," in contrast to engineering's concern of "how things ought to be in order to attain goals, and to function." Similarly, Vincenti (1990, pp. 134–135) argues that although engineering research is similar to science (both conform to natural laws, diffuse through similar mechanisms, and are cumulative), they differ because the ultimate goal of science is the understanding of nature, but for engineering is the creation of artefacts.

However, this simplistic distinction is true only for a simplistic view of science and engineering. The situation can be more complex. Engineering researchers often create and test descriptive theories about materials or structures by performing controlled experiments, for use in the analysis and design of artefacts. Rapp (1981) argues for the view that engineering research is mostly descriptive when formulating and empirically testing theories. Vincenti (1990, pp. 195–198) also says that descriptive knowledge of how things are is a fundamental kind of engineering knowledge. On the other hand, scientists sometimes create and test artefacts to meet precise requirements, for use as scientific instruments. Regardless, the over-arching difference remains. Brooks (1996, p. 62) says on this, "A high-energy physicist may easily spend most of his time building his apparatus; a spacecraft engineer may easily spend most of his time studying the behavior of materials in vacuum. Nevertheless, the scientist *builds in order to study*; the engineer *studies in order to build.*"

Houkes (2009) identifies a objection to arguments for the epistemic emancipation of engineering from science resting on the 'truth vs usefulness' (TU) intuition (that science aims for truth whereas engineering aims for usefulness). The objection is that if one cannot rule out an instrumental notion of science, then science may ultimately be evaluated by its usefulness, and so not be easily distinguished from engineering. My counter is to refine the TU intuition: engineering theories are not primarily evaluated by their usefulness, but are instead *about uses*, and are evaluated by their validity in corresponding with those uses. It does not matter for the epistemic emancipation of engineering from science whether scientific theories are evaluated instrumentally or not. Science does not in any case make claims about requirements.

4.2 Engineering is an Applied Science?

If engineering is not a science, might it still be an applied science? Engineers do often apply or adapt scientific theories, and early work on the philosophy of technology equated technology (including engineering) with applied science (Bunge 1966). Historians and philosophers have more recently taken a different a view. Layton (1971) describes as a misconception the idea that engineering is merely applied science, and explores the consequences of that misconception on policy. van de Poel (2010, p. 5) summarises a number of recent philosophical papers on the relationship between science and engineering, saying there is "... one point of agreement: engineering is not applied science."

As with engineering, there is no widely accepted definition of applied science. Applied science and engineering have several commonalities. For example, both draw on general scientific theories, and develop specialised forms which are limited to a narrow scope of application. These limited theories would not be acceptable as ideal theories within pure science. Also, both are concerned with the development and use of *applicable* theories, and so are both concerned with understanding phenomena in the context of some requirement.

However, there are differences. While applied scientists and engineers both perform analyses of designs for artefacts, engineers are typically more concerned with the creation and realisation of those designs. Although both seek to analyse artefacts' behaviour with respect to requirements, engineers are in many countries legally privileged and regulated in their ability to provide assurances about artefacts; particularly about safety or reliability. Engineers are also typically more concerned than applied scientists with the discovery and characterisation of requirements.

That engineering does not always apply science is evident from historical cases where engineering discoveries have preceded scientific explanations. Layton (1971) considers this issue in depth, and notes cases in elasticity, hydrodynamics, and thermodynamics where engineering discoveries have transferred to science. An important case is Carnot's theory of the performance of engines. Carnot was a professional engineer, and the Carnot heat engine was an idealised engineering theory intended to be applicable to a range of steam engines. Layton discusses that it was formulated not as a scientific explanation of thermodynamics, but instead to express an idealised design principle. Carnot's theories were later revised and further generalised by others (Clausius, Kelvin) and adopted into science as part of a more general theory of thermodynamics.

Two other reasons for why engineering is not applied science have been presented earlier, in the arguments for why engineering is not science. Firstly, engineering accepts and uses phenomenological theories and methods which are undesirable within science. Secondly, some engineering analyses address qualities (including cost and socio-technical issues) that are not considered in the sciences. These kinds of theories are not acceptable in science and so will not be available to be used by applied scientists.

4.3 Engineering is Mechanically-Applied Knowledge?

Sometimes it is said that after basic research is completed, the creation of an artefact is “just a matter of engineering”, i.e. a straightforward or mechanical application of that knowledge. Reality is usually rather different; engineering research and practice are usually exploratory and creative.

Firstly in engineering research and practice, requirements are often not initially well understood. Rapp (1981) identifies sources of engineering requirements, including customers in the market, and regulatory political institutions. However, many requirements for the use of an artefact may not initially be known by anyone, including the users. Engineers do not create the underlying needs, but often discover them. As repeatedly discussed by Vincenti (1990) and Johnson (2009), engineers are usually closely involved in the explicit definition of requirements specifications. The explication and validation of requirements for artefacts, and the refinement of those requirements specifications, is part of the growth of engineering knowledge. Knowledge about requirements and how to best represent them can evolve in conjunction with, or subsequent to, the initial creation of artefacts intended to address those requirements.

Secondly, design is a creative act that should not be limited by simple mechanism. The knowledge of how to create designs is different to and not necessarily apparent from the knowledge of how to predict the performance of artefacts. The distinction of design from analysis has been widely noted by previous authors. Petrowski (1996, p. 2) notes that mathematics and science do not directly derive designs. Vincenti (1990), following Polanyi (1958), says that scientific laws “in no way . . . contain or by themselves imply the [operational] principle” of an artefact. Nevertheless, whether human creativity is required to produce designs is not entirely black-and-white. Simon (1969, pp. 118–130) describes how computers can search for candidate designs. This may be ‘heuristic’ in that the generated design candidates require further theoretical analysis and empirical testing, but increasingly, theoretical analyses can be incorporated directly into computer-supported search or optimisation mechanisms. Regardless, it is possible that potential designs may lie outside the design space encoded in such computer programs.

4.4 Engineering is Trial and Error?

One pejorative misconception of engineering is that it is just ‘trial and error’. It is true that engineers perform trials, and these trials may discover errors. However Vincenti (1990, pp. 48–49), quoting Campbell (1974) and Popper (1974), argues that this ‘blind’ search is not random. Just as a blind person can feel their way incrementally through an unknown room, so too scientists and engineers can develop knowledge about unknown phenomena and the performance of artefacts.

Consider the engineering method of parameter variation (Vincenti 1990). This is the systematic exploration of a design space, by varying the value of design parameters within that space. The method runs repeated trials of different parameter configurations, most of which will not perform as well as the best configuration. So it is in some sense is ‘trial and error’. Nonetheless, underlying the method are creative and ever-improving theoretical ideas about how to parameterise the design space, what performance characteristics to measure, and the possible impact of the parameters on performance. Engineering knowledge guides these trials: the results are initially unknown, but the method is not random.

4.5 Engineering is Technology?

Most modern technologies are developed and realised through engineering research and practice. Engineering usually deals with technologies, but is engineering research or practice the same as technology? van de Poel (2010) summarises various conceptions of technology (as artefacts, as activity, or as knowledge and purposive action), leading to various positions on its relationship to engineering (respectively, as a product of engineering, as the performance of engineering, or as a body of engineering knowledge and skill). Bo-cong (2010) argues to distinguish between technology because they have different activities, achievements, thinking styles, communities, standards, institutions, and cultures.

It is clear that technology and engineering are not identical, because some technologies can be developed and used without engineering, through craft activity or through improvisation. Davis (1996) notes that technological development has been occurring since pre-historic times, whereas engineering is more recent. For example, a stick used as a club is a primitive technology, which can be developed and used without objective engineering analyses. On the other hand, engineering is not just a subset of technology, because engineering analyses are sometimes applied to naturally occurring situations. For example, engineers might hydrologically assess the requirement that a community living in a flood plain be safe from flooding. The object under analysis here (a plain) is not a technology. What distinguishes engineering from technology is methodology—a systematic approach for the use and growth of objective knowledge about how the physical world can be made to meet requirements.

5 A Model of Engineering Knowledge

What kind of thing is engineering knowledge, and how is it structured? In this paper I focus on objective engineering knowledge, which is communicated as written text, diagrams, and mathematics, and which is typically transmitted through university curricula, textbooks, patents, technical reports, journal papers and conference presentations. In the engineering of specific artefacts in practice, requirements specifications and designs are also elements of the objective knowledge base. Taxonomies of engineering knowledge (Houkes 2009) include other kinds of knowledge, but these are not covered by my models. In this section I propose a model that represents the inter-relationships between the three key elements of engineering noted in section 2: artefacts (and their designs), artefacts' uses to meet requirements (and specifications of this), and engineering theories that support claims that artefacts' uses meet their requirements. The structure of the model underlies the logical treatment of engineering theories in section 6.

The model uses Popper's (1972; 1977) *three worlds* ontological framework. World 1 is the world of physical entities and phenomena. World 2 is the world of mental or subjective states and events. World 3 is the world of objective content: knowledge and products of thought that can be explicitly recorded or spoken. The worlds are not distinct, because mental states have a physical basis and because objective knowledge can be understood and can be physically represented. There are direct interactions between World 1 and World 2 (e.g. sense perception and the will to act); and between World 2 and World 3 (e.g. representation and understanding). Interactions between World 1 and World 3 (e.g. prediction of empirical phenomena by theory) are only indirect. They are mediated by the second World of human understanding and intention.

The model of engineering knowledge proposed here is depicted in Figure 1. The model makes explicit that engineering theories are about, and connect, both requirements on usage situations, and artefact performance. It abuts two instances of Popper's framework. One instance represents the relationship between (changes to) the situation of an artefact's potential or actual use in the world, and its formalisation as a requirements specification. The other instance represents the relationship between the artefact's presence and performance in the world, and its formalisation as a design. The two instances of Popper's framework are connected by reasoning within World 3 about why designs meet specified requirements, and therefore (according to an engineering theory) why actual artefacts (when those artefacts correspond to the designs) can bring about required changes in the usage situation (when the situation and changes correspond to the specified requirements). Of course, the two instances of each of the three worlds is not a claim that there are now six worlds! Instead, the two instances merely represent different parts of each of the three worlds.

This model does not distinguish between worlds teleologically nor by discipline, and so is in contrast with Chakrabarty (2012) who claims that manufactured artefacts cannot be part of World 1 because they are not natural, and is in contrast with Bo-cong (2010), who proposes a 'fourth world' of physical man-made objects. My stance is consistent with Popper (1978, pp. 162–163), who explicitly admits designs as ordinary World 3 objects and artefacts as ordinary World 1 objects.

I hold that the intentional nature of an artefact is not inherent in the physical object, because people can use naturally-occurring (intention-free) objects for purposes, and can use existing devices (built for old purposes) for alternative purposes. However, the purpose can be *related* to the object. My conception is somewhat similar to the view of Kroes (2002, pp. 294), who defines a composite notion of 'technical artefact' as "a physical object

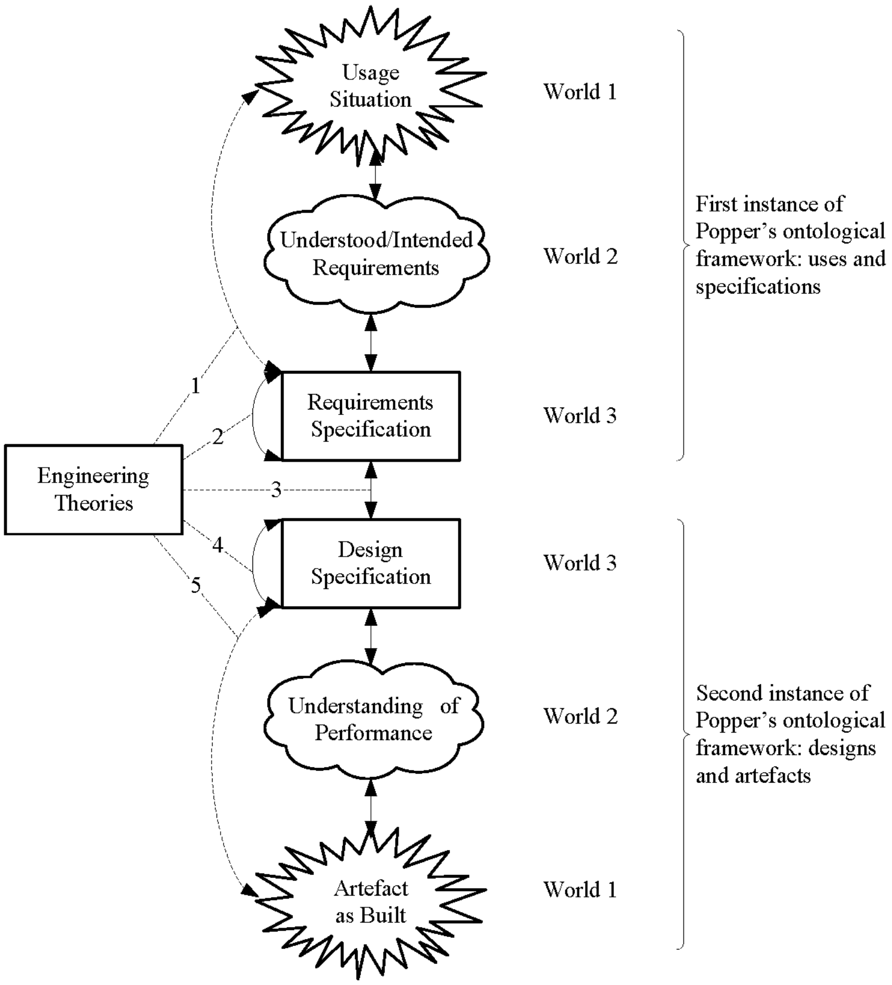

Fig. 1 Elements of Engineering within Popper's Three Worlds. The numbers 1–5 indicate the roles played by engineering theories.

with a technical function. This characterisation of a technical artefact makes it a hybrid kind of object which does not fit in either the physical or the intentional conceptualisation." I would say that artefacts as built fit a physical conceptualisation, and artefacts as used fit an intentional conception. Still, like me, Kroes does not consider that the purposes are intrinsic to the physical object.

My model is more directly similar to the views of Houkes and Vermaas (2009) and Houkes et al. (2011) on the dual-nature of artefacts, who describe intentions as relative to a *use-plan* for the artefact. Thus the top half of Figure 1 deals with use-plans, the bottom half with physical artefacts, and their relation is achieved or justified by engineering theories linking high-level requirements specifications to low-level designs. Linking theories include what Polanyi (1958) calls ‘operational principles’: rules for achieving a material advantage. Understanding this material advantage (the change being brought about in the usage situation) is important to understanding the operational principle; knowledge of an artefact’s behavior is not in itself sufficient to know how well it can be used to make a needed change in the world.

In engineering, ‘requirements’ may be variously conceived as changes to be brought about in usage situations, as intended or perceived needs, or as written specifications. These three different conceptions of requirements correspond to the three worlds respectively. They are also associated with different conceptions of ‘quality’ in engineering: ‘fit for purpose’, ‘functions as intended’, or ‘functions as specified’, respectively. In Garvin’s (1984) survey of definitions of product quality, these are called user-based, product-based, and manufacturing-based definitions. Something is a ‘need’ when mentally judged (in World 2) to be one. However, the potential or actual use of an artefact is a World 1 thing, and the physical situation which is changed by the use of an artefact (which has or can be judged to be a problem situation) is also in World 1. A description of the needs for the physical situation may then be rendered as a requirements specification (World 3). This is somewhat analogous to science, where physical stimuli (World 1) may judged (World 2) to be observations of physical phenomena (World 3). In science, World 1 is taken to be prior, because science is descriptive. Engineering theories are often used prescriptively, in which case World 2 is prior (subject to World 1 constraints on feasible realisation). Regardless of the reference point, what is important for engineering purposes is striving for the worlds to be in correspondence.

In general, requirements might be infeasible. (Rapp 1981) says that realisable requirements, like scientific theories, are constrained by [p. 46] “logic and the laws of nature”. However, within that broad space, requirements are otherwise somewhat contingent, constrained by whether their consequences are deemed to be acceptable. Requirements include not just the main function of an artefact, but also acceptable side-effects and acceptable operational and environmental conditions of use. Rapp (1981) notes that even if a technological action achieves its main goals, it may be abandoned if its side-effects or secondary consequences are unacceptable. (For example, a laptop computer might run standard software, but be abandoned if it becomes painfully hot.) Similarly, requirements also encompass the range of acceptable environmental conditions for the use of an artefact. (For example, most watches do not work underwater, but this would not be an acceptable environmental constraint for a scuba diver’s watch.) Environmental assumptions about the context for the future use of an artefact can never be completely known. For natural disasters, engineers must make reasonable assumptions about the likelihood of disasters of particular magnitudes. When guarding against failure of an artefact because of a hostile attacker, engineers must make reasonable assumptions about the resources available to attackers.

Figure 1 shows five roles played by engineering theories, for connections within World 3 and between Worlds 1 and 3. Theories are themselves objective knowledge (World 3) and so must only contain World 3 elements, but these may be interpreted empirically. Any individual theory may play one or more of the five roles:

1. characterisations of changes to be brought about in usage situations, represented (i.e., formalised, documented) as requirements specifications;
2. claims about how high-level requirements specifications can be decomposed to lower-level requirements specifications;
3. claims about how requirements specifications can be satisfied by a design;
4. claims about how high-level designs can be decomposed to lower-level designs; and
5. characterisations of artefacts and their behaviour, represented (i.e., formalised, documented) as designs and descriptions of behaviour.

Theories playing roles 1 and 5 are directly empirical, because they are claims (in World 3, as understood in World 2) about the real world (World 1, as understood in World 2). Theories playing the other three kinds of roles instead are only indirectly empirical, because they are claims (in World 3, as understood in World 2) about how theory elements (in World 3, as understood in World 2) are related to each other. They are indirectly empirical because their claims are only vicariously connected to the real world through theories playing roles 1 and 5. Theories playing roles 2 and 4 may be recursively applied over a hierarchy of requirements or design decompositions. The five roles are related to logical formulae representing engineering theories in section 6. They are also used in the subsequent paper (on methodology) as a taxonomy of falsification and responses to falsification in engineering.

The model describes entities, relationships, and theories within engineering, but is not a process model for engineering design. Some engineering problems may be resolved in order from the top of the diagram to the bottom—from a physical situation judged to have some unmet need, through to the realisation of a design as an artefact whose use would satisfy the need. However, the engineering process can play out in other ways. For example, the extraction of mineral ore might proceed largely in reverse. This might start with a number of potential artefacts (candidate mine sites) as a given, followed by the descriptive creation and engineering analysis of 'designs' for the extraction of ore from discovered mineral deposits. Or, engineers might perform a 'design recovery' on an extant artefact as part of reverse engineering, to reconstruct a lost design or to create a more accurate new design. All of these processes are constrained by the need for explicit justifications for rational arguments supporting claims that artefacts will perform to meet their requirements. The model can be seen as a structure for these arguments, but not the process which constructs these arguments.

My model is not a taxonomy of all kinds of technological or engineering knowledge. Nonetheless, it is comparable to some of the taxonomies listed by Houkes (2009). My model is most similar to the taxonomies from de Vries (2003) and Ropohl (1997). Theories playing role 1 are similar to de Vries' 'Functional-nature knowledge' and cover parts of Ropohl's 'Socio-technical understanding'. Theories playing role 5 are similar to de Vries' 'Physical-nature knowledge' and Ropohl's 'Technological laws'. The overall connection between requirements and design played by theories in roles 2–4 are similar to de Vries' 'Means-ends knowledge (which Houkes calls 'Knowledge of physics-function relation'). Role 3 is similar to Ropohl's 'Functional rules' and role 4 to Ropohl's 'Structural rules'. For tacit knowledge, de Vries' category of 'Action knowledge' (which Houkes calls 'Process knowledge') and Ropohl's category of 'Technical know-how' have no direct analogue in my model. However, objective procedural knowledge can be captured as descriptions of instructions in theories playing roles 2–4. Vincenti's (1990) categories are only roughly related to my model: 'Fundamental design concepts' and 'Design instrumentalities' would include theories playing roles 3 and 4, 'Criteria and specifications' would include roles 1 and 2. The categories 'Theoretical tools' and 'Quantitative data' could include theories playing any role, while 'Practical considerations' is only partly covered by propositional theories playing any role. Faulkner's (1994) categories don't neatly align with my model: 'Related to the natural world' corresponds to role 5, but 'Related to final product' includes theories playing roles 1 and 5, and 'Related to design practice' includes theories playing roles 1–4. 'Related to experimental R&D' could include theories of any role, and 'Related to knowledge' has no analogue to any of the roles. Overall, my model distinguishes different kinds of objective knowledge about requirements, artefacts, and their relationship, but does not have a straightforward treatment of tacit knowledge (see section 7). It captures declarative engineering theories, but captures procedural objective knowledge only when it is embedded in some indicative claim.

6 Engineering Theories as Logical Theories

The deductive-nomological view of scientific theories as logical theories is an abstract view of scientific knowledge well-known within the philosophy of science. Here I present an analogous logical view of engineering theories which is ontologically grounded in the three worlds model of the previous section. The following can serve as a general logical form for a rule in a scientific theory:

$$A(x) \vdash P(x)$$

A scientific theory claims that for all states of the world x where antecedent conditions A apply, then predicted phenomena P occur. Properties of observed actual phenomena must be within the theory's predictions. x may refer to an individual state of the world, or a collection of states constrained by A.

In section 2 I discussed the three recurring elements of definitions of engineering: artefacts (and their designs), artefacts' requirements for use (and their specifications), and engineering theories that support claims that artefacts meet their requirements for use. So, terms for designs and requirements should appear within engineering theories. The ontological framework in section 5 describes these elements of objective content, their interpretation as real-world entities, and the correspondence relations between them as claims supported by engineering theories. Simon (1969, p. 5) lists three terms required for the analysis of artificial things: "... the purpose or goal, the character of the artefact, and the environment in which the artefact performs." In addition to designs and requirements, we can introduce a term for the environment, which like antecedent condition A in scientific theories limits the scope of engineering theories. Although I formally distinguish the environment from requirements, the acceptance of constraints on the environment is usually taken within engineering to form part of the broader requirements for an artefact. The following can serve as a general logical form for engineering theories:

$$[E(x,a); D(a)] \vdash R(x,a) \tag{1}$$

That is, an engineering theory claims that for any state of the world x, including an artefact a, where acceptable environmental conditions E apply in the world and to the artefact, and where the artefact fits a design D, then requirements R will be satisfied. When applied to reason about a specific artefact, the requirements for the artefact must be within the theory's predicted performance of the artefact R, and the actually-acceptable limitations on the specific operating environment must contain the theory's environmental conditions E. Designs are usually abstractions, often expressed in a form that is consistent with relevant analytical theories. Multiple artefacts may satisfy a single design, and a single artefact may satisfy many designs.

Formula 1 can be decomposed using *modus ponens*:

$$[E(x,a); D(a)] \vdash B(x,a) \tag{2}$$

$$[E(x,a); D(a)] \vdash B(x,a) \rightarrow R(x,a) \tag{3}$$

Engineers may use one set of rules (formula 2) to predict artefacts' behavior B, then separately reason (formula 3) about how that behavior satisfies requirements R, thus deriving the overall claim (formula 1). This problem decomposition allows the development and use of generic theories to predict performance. The claims of a very general theory are unlikely to be identical to particular requirements specifications R, but may entail them.

Hoare (1996) and Rushby (2013) present logical formulations of engineering theories and safety arguments which are generally consistent with this view. (However, Rushby also encodes a kind of defeasible logic to accommodate possible defeaters, which I regard as methodologically unacceptable, as discussed in section 6.1.) Hoare sketches an example of an industrial control system: a tank containing a liquid, with input and output valves. Here I adapt Hoare's example to my scheme above. For discussion I consider only one safety condition—Hoare discusses how logical conjunction can be used to separately treat individual requirements, but this is not shown here. Hoare provides a safety specification on the level of liquid v in the tank: $minv \leq v_t \leq maxv$ for all times t after starting. Let us call this condition $within\_limits_t$. From the operator's perspective, the tank should be safe during operation, but an untrained operator will not necessarily know about or understand issues associated with the level of liquid in the tank and how that impacts on safety. Adapting the formalisation of safety arguments by Rushby (2013), we can instead define a condition for the need for safety in use, safe_t. This is only vaguely defined here, and in engineering practice, safety requirements are usually concrete claims about there being no loss of life or serious injury. Still, let us take it to be R, and take Hoare's specification as B. So the strategy to ensure safety is $\mathit{within\_limits}_t \rightarrow \mathit{safe}_t$ for times t, which is the consequent in formula 3. This has the status of a conjecture, or claim, and may be falsified. For example, the system may become unsafe if the tank ruptures. Rushby expands this logical treatment of claims to handle all identified hazards. Nonetheless, such claims remain tentative because some hazards may remain unidentified. Hoare notes some elements of the environmental conditions E (e.g. that the flows are liquid) and design constraints D (e.g., that valves settings are within defined limits). Equations predicting flow are also given, which depend on the setting of the output valve and the volume-dependent pressure in the tank. These are like lemmas supporting formulae 2.

So, while we can look at engineering theories from a logical perspective, we see that the terms x, E, D, B, and R all have an empirical interpretation. They can be instantiated with empirical observations, i.e. judgements that measurements or perceptions of phenomena are characterised by those terms. The empirical validity of these terms as constructs is critical to sustaining the overall empirical validity of the engineering theory. The three worlds ontological framework from the previous section outlines the empirical grounding of these terms. In terms of the roles of engineering theories shown in Figure 1, formula 2 plays role 5 (artefact's behavior), and formula 3 plays role 3 (requirements satisfied by a design). Formulae 1 and 3 also play role 1 (requirements as specified), by specifying requirements R as the goal. Theories of roles 2 and 4 allow for the (recursive) decompositions of formulae 2 and 3 respectively. This is not illustrated here, but Hoare (1996) elaborates a logical perspective on design decomposition.

The use of empirical theories for engineering analyses was allowed by Popper (1972, p. 352). He discussed how technical application of scientific theories can proceed as an 'inversion' of scientific application. (Inverted because the theory is used prescriptively, not descriptively.) Given initial conditions (e.g. perhaps the design of an artefact and also environmental assumptions), and universal theories, behaviours of the artefact can be predicted to arise. The schematic form of theories in engineering is an instance of the general form for scientific theories, and so the logical position is the same: such theories can be deductively falsified by a counter-example, but cannot ever be deductively verified by confirming observations. I further discuss the falsification of engineering theories in a subsequent paper (on methodology).

6.1 Logically-Uninterpreted Conditions in Engineering Theories

Theories have conditions which limit the scope of their application. Many of these play analytical roles; they are worked on as part of calculations under the theory, and modulate its predictions. However, I note that some conditions in engineering theories do not play any substantial analytical role in the calculations performed within the theory. Although such conditions may at first glance seem spurious, and indeed might be for a fundamental scientific theory, they are important for ensuring the validity of phenomenological theories with highly limited scope. They carry an inter-subjective empirical interpretation that limits the application of the theory to defined real-world situations.

Consider engineering theories with limits on acceptable temperature ranges. Such theories are only applicable within those ranges, but the temperature-related conditions are not necessarily logically-interpreted. For example, an engineering theory related to the performance of steam turbines may be limited to a specific range of operating temperatures, but within that range provide rules of calculation to determine how the performance of the turbines varies with the operating temperature. In this case, the temperature condition would be a logically-interpreted condition. However, another idealized engineering theory concerned with water pumps might use fluid-flow equations that carry an assumption about temperature that restricts the application of the theory to operating temperatures where water is liquid, but within that temperature range the operating temperature may not be used by the rules of the approximate theory to vary the predicted performance of the pump. In this case, the temperature condition would be a logically-uninterpreted condition.

Such conditions are ‘extra-logical’ because they only have impact on the operation of the theory through their interpretation outside of the formal axiomatic system. From a formal perspective, they are uninterpreted constants, and are thus free to be given any interpretation. Nonetheless, when used as part of engineering theories, I agree with Popper (1959, p. 53) that primitive terms in a theory should not be left implicitly defined. Popper (1959, p. 61) rejects this because he sees it as a ‘conventionalist stratagem’ whereby scientific theories are left as logical constructions implicitly defined by the world, rather than standing in tentative correspondence to it. I reject it for engineering theories too, even if they are only phenomenological. Engineering theories will not necessarily stand in deep correspondence to the world, but should be reliably inter-subjectively testable and must reveal their failure when engineering failures occur. This can only happen if the conditions under which an empirical theory may be severely tested are explicitly defined.

As mentioned earlier, Rushby (2013) uses logically-uninterpreted constants as antecedent conditions to represent possible defeaters. In addition to these conditions not being logically-interpreted, they are also not explicitly empirically interpreted. This is the stratagem rejected by Popper for science, and by myself for engineering. From the perspective of critical rationalism, the overall growth of knowledge is in a sense defeasible because theories are tentative. However any individual theory must be falsifiable because otherwise it would admit any observation. Rushby's implicit-defeaters are only interpreted empirically *post-hoc.* Only by being clearly falsified are we able to deduce that something is wrong with our theory, and begin the search for a better one.

Logical assumptions play a direct role in the calculations of a theory, and so are naturally explicit. However, in empirical theories, it is also critical to explicitly identify important logically-uninterpreted assumptions and to give explicit empirical interpretations for them. If left implicit, such assumptions are like *ceteris paribus* conditions. Cartwright (1983, p. 45) says "The literal translation is 'other things being equal'; but it would be more apt to read '*ceteris paribus*' as 'other things being *right.*" Things rarely go right just by themselves—a fundamental principle of engineering might be Murphy's Law: "Anything that can go wrong will go wrong." The engineering mind-set must consider the range of ways in which an artefact may fail. Explicating assumptions helps engineers to ensure that things 'go right' in use. In engineering, assumptions carry through to become part of the defined operating conditions for an artefact, and must be allowable under the artefact's requirements.

6.2 Objections to Logical View of Engineering Theories

An objection may be raised that logic is not how engineering works in practice. Engineers don't write their procedures or rules of thumb as theories, let alone as logical formulae! Nonetheless, one would not deny it was engineering purely on this basis, if engineers did start to do this. This is also true of scientific theories—formal logic is not the actual language of science. The same point may even be made about mainstream mathematical practice. The view of engineering theories as logic is abstract in the same way as Popper's view of science, or as an idealised view of mathematics. A logical view of theories preserves a deductively-sound basis for rational reasoning, which one could in principle fall back to to clarify the details of theoretical arguments in mathematics, science, and engineering. In fact, the calculational rules used by engineers are often formally documented, sometimes so rigorously that they can be encoded as computer algorithms. These rules or algorithms can be considered to be logical theories, and calculations according to them can be considered to be deductions within those theories.

Another objection is that a deductive view may be fine for (descriptive) science, but is not appropriate for (prescriptive) engineering. As Polanyi (1958, p. 175) notes, "Knowledge can be true or false, while action can only be successful or unsuccessful, right or wrong." If engineering is seen as a technological action, then it cannot be defined propositionally. Ryle (1945) says that it is nonsensical to ask whether technological instructions or rules are true or false. My view is that while engineering acts may be imperative, engineering theories are indicative. Technological instructions are codified as designs or operational constraints for artefacts. Is the artefact built correctly according to the design, or is the design a valid representation of the artefact? As noted earlier, designs are neither commands nor propositions. Whether a design is used to create an artefact, or an existing artefact is reverse engineered to reconstruct a new design description, the design is in either case a term in an empirical theory about the artefact. The correspondence of the design with the artefact can be tested empirically in both cases. What is judged are the results of the actions of building the artefact, not the imperative to act.

Koen (1988) objected to viewing engineering theories in logical terms, and instead calls them 'heuristics'. There certainly are heuristics within the body of engineering knowledge. For example, design heuristics encode plausible rules of how to create candidate designs. Such heuristics I call 'engineering theories' if and only if they are also claims that artefacts designed using those heuristics meet requirements. Koen says that there are four barriers to viewing engineering theories in logical terms. Koen's first point is that engineering theories do not guarantee a solution. Indeed, no empirical theory guarantees truth or a solution to a physical problem, not even scientific theories. We can still free to regard empirical theories in logical terms as conjectures. Koen's second concern is that engineering theories can contradict each other. This is not a logical problem if one of them is false. Such cases are normal in the growth of knowledge, and are resolved by determining which theories are false, then rejecting or revising them. However, even true approximate theories may give different predictions about the same phenomena that are nonetheless each valid within their claimed limits. Then the different results are not contradictory: instead a new stronger theory may be created by taking the intersection of their predictions. (If this is empty, then one or both must have be false.) Or, a weaker theory may be created by taking the union of their approximate predictions. Koen's third point is that engineering theories can reduce the time to solve a problem. This is a key instrumental property, but is not a logical issue. Koen's final concern is that the acceptance of engineering theories depends on them being useful, in contrast to scientific theories whose acceptance depends on correspondence with reality. From my viewpoint this is a concern about engineering theories being phenomenological and having a limited scope of applicability, but neither of these issues are a barrier to seeing theories in logical terms. In logical terms, the environmental conditions in engineering theories are merely often stronger that in scientific theories.

7 Some Limitations of the Proposals

Models are idealisations, approximations or analogies, and carry limitations on what or how much they say about a physical situation. Here I identify and discuss some of the limitations of the models proposed in this paper.

Ethics and Societal Norms The models may provide a partial framework to discuss epistemological dimensions of ethical issues, but do not themselves talk directly about ethical issues. Who decides on requirements, and which requirements should be satisfied?

Different people or groups want to bring about different changes in the world, and so have different needs and can accept different kinds and levels of side effects and operational constraints. As a simplifying move in this paper, I have largely avoided the issue of societal norms and their relation to technology and requirements. Here, societal norms are taken to be absorbed as part of individuals' mental states, and so are only implicitly recognised, as World 2 needs. Requirements can be socially determined, but as will be discussed further in the subsequent paper (on methodology), requirements on usage situations are also physically constrained. Needs for usage situations often only become understood or better known through unexpected physical consequences experienced in use.

Modern engineering brings new ethical challenges which have significant epistemological dimensions. Wulf (2004) warns that some modern systems are so complex that engineers are unable to predict their behavior. In some cases this is not just due to a lack of knowledge about the systems, but instead because the problems are 'wicked' (Rittel 1972) or because the systems exhibit discontinuous or emergent behavior of a kind which is physically impossible to predict. How can engineers ethically create such systems, when there is no strong basis for justifications that the systems will meet their requirements?

Probabilistic Theories The view of engineering theories as classical logic, discussed in section 6, does not seem to easily admit probabilistic claims and approximations, which are common in engineering. One could axiomatize probability theory in a classical logic and use that to represent empirical theories. However a common criticism of critical rationalism, particularly from Bayesians (Howson and Urbach 2006), is that Popper does not deal well with probabilistic scientific theories. One possible response is to give the general framework of critical rationalism a Bayesian treatment (Constant 1999; Gelman and Shalizi 2012), and then the general framework of Figure 1 might similarly stand. I have not explored these issues in this paper.

Tacit Knowledge The models in this paper focus on objective knowledge in engineering. However as noted by many authors (Vincenti 1990; Ferguson 1992; Houkes 2009), various kinds of tacit knowledge are also important within engineering. For example, Vincenti (1990, p. 208) lists six categories of engineering knowledge, two of which have significant tacit elements and which may not neatly fit into my proposed model: practical considerations, and design instrumentalities (including design know-how).

Tacit knowledge is normally be thought to be personal and mental, and thus be in World 2. It is normally contrasted with objective knowledge (in World 3). However, one might argue that there are varieties of tacit knowledge, including skilled muscle memory (in World 1), or even tacit knowledge encoded as easily-actionable uses in the affordances (Gibson 1979) of physical artefacts (World 1). Tacit (as 'implicit') knowledge might also arguably include unembodied World 3 objective knowledge—logical consequences of theories that have yet to be understood or documented.

This paper leaves as an open issue a complete treatment of all kinds of engineering knowledge, and in particular a treatment of tacit knowledge.

8 Conclusions

Engineering, like science, is a rational empirical discipline. As in science, the key criterion for engineering theories is empirical validity. Although engineering often draws on science, it is not science, and is not merely applied science. Engineering has its own kinds of knowledge, which are about different kinds of claims than scientific knowledge, and have different characteristics. Unlike scientific theories, it is sufficient for engineering theories to be phenomenological. Engineering theories may also be highly approximate or have a very narrow scope, just as long as they are precise enough and broad enough in scope to be applicable to the analysis at hand of a particular design for particular requirements. Competing engineering theories also have different 'instrumental properties', and so require different levels of time, expertise, or cost to use. Because of these multiple dimensions, the body of engineering knowledge consists of multiple concurrently-held engineering theories, each with different precision, scope, and instrumental properties.

Perhaps the most significant difference is that engineering theories deal with requirements, which are not part of the ontology of scientific knowledge. There are three recurring elements in definitions of engineering: artefacts, requirements, and engineering theories. I have proposed a model of objective engineering knowledge using Popper's three worlds ontological framework that makes explicit that engineering theories express claims that an artefact (represented in the theory by a design) will perform in a way that satisfies its requirements for use (represented in the theory by a requirements specification). In the proposed model, two instances of the three worlds capture usage situations and artefacts respectively. Requirements on usage situations are represented as requirements specifications, and real world artefacts are represented as designs. Requirements specifications and designs are linked in the third world of objective content by reasoning, using engineering theories. The logical view of engineering theories presented in this paper provides an abstract formulation of the correspondence relationships between requirements and artefacts that are shown in the three worlds model. I call each of these relationships a 'role' that can be played by engineering theories.

The ontological framework introduced here is used in a subsequent paper which examines methodological issues in the growth of engineering knowledge. Building on the logical view of engineering theories presented in this paper, I explore falsification of engineering theories. I use the five roles played by engineering theories in the three worlds model as a taxonomy of falsification and responses to falsification in engineering. Falsification of engineering theories (as logical theories) drives the growth of knowledge within the body of engineering knowledge, and also allows a treatment of presumptive anomalies (Constant 1984) and engineering failures. The taxonomy uses the five roles to locate the sources of falsification by identifying which correspondence relations are invalid. As in this paper, the epistemology of engineering is investigated in its own right, both to better understand engineering, and also as contrastive with science to better understand epistemology.

References

Bo-cong, L. (2010). The rise of philosophy of engineering in the east and the west. In van de Poel and Goldberg (2010), pages 31–40.

Boon, M. (2011). In defense of engineering sciences: On the epistemological relations between science and technology. *Techné: Research in Philosophy and Technology*, 15(1):49–71.

Brooks, Jr, . F. P. (1996). The computer scientist as toolsmith II. *Communications of the ACM*, 39(3):61–68.

Bunge, M. (1966). Technology as applied science. *Technology and Culture*, 7(3):329–347.

Campbell, D. (1974). Evolutionary epistemology. In Schilpp, P. A., editor, *The Philosophy of Karl Popper*, volume I. Open Court.

Cartwright, N. (1983). *How the Laws of Physics Lie*. Oxford University Press.

Chakrabarty, M. (2012). Popper's contribution to the philosophical study of artifacts. In *Philosophy of Science Association 23rd Biennial Meeting*.

Clausen, J. and Cantwell, J. (2007). Reasoning with safety factor rules. *Techné: Research in Philosophy and Technology*, 11(1):55–70.

Constant, II, E. W. (1984). Communities and hierarchies: Structure in the practice of science and technology. In Laudan, R., editor, *The Nature of Technological Knowledge*, pages 27–46. D. Reidel.

Constant, II, E. W. (1999). Reliable knowledge and unreliable stuff. *Technology and Culture*, 40(2):324–357.

Cuevas-Badallo, A. (2005). A model-based approach to technological theories. *Techné: Research in Philosophy and Technology*, 9(2).

Davis, M. (1996). Defining "engineer": How to do it and why it matters. *Journal of Engineering Education*, pages 97–101.

Davis, M. (2010). Distinguishing architects from engineers: A pilot study in differences between engineers and other technologists. In van de Poel and Goldberg (2010), pages 15–30.

de Vries, M. J. (2003). The nature of technological knowledge: Extending empirically informed studies into what engineers know. *Techné: Research in Philosophy and Technology*, 6(3).

de Vries, M. J. (2010). Engineering science as a "Discipline of the particular"? Types of generalization in engineering sciences. In van de Poel and Goldberg (2010), pages 83–93.

ECPD (1947). *Canons of ethics for engineers*. Engineers' Council for Professional Development.

Faulkner, W. (1994). Conceptualizing knowledge used in innovation: A second look at the science-technology distinction and industrial innovation. *Science, Technology, & Human Values*, 19(4):425–458.

Ferguson, E. S. (1992). *Engineering and the mind's eye*. The MIT Press.

Fetzer, J. H. (1988). Program verification: the very idea. *Communications of the ACM*, 31(9):1048–1063.

Garvin, D. A. (1984). What does "product quality" really mean? *Sloan Management Review*, 26(1):25–43.

Gelman, A. and Shalizi, C. R. (2012). Philosophy and the practice of Bayesian statistics. *British Journal of Mathematical and Statistical Psychology*, 66(1):8–38.

Gibson, J. J. (1979). *The Ecological Approach to Visual Perception*. Lawrence Erlbaum Associates.

Goldberg, D. E. and McCarthy, N., editors (2008). *Workshop on Philosophy and Engineering (WPE 2008)*. The Royal Academy of Engineering.

Hoare, C. A. R. (1996). The logic of engineering design. *Microprocessing and Microprogramming*, 41:525–539.

Houkes, W. (2006). Knowledge of artefact functions. *Studies in History and Philosophy of Science*, 37(1):102–113.

Houkes, W. (2009). The nature of technological knowledge. In Meijers (2009), pages 309–350.

Houkes, W., Kroes, P., Meijers, A., and Vermaas, P. E. (2011). Dual-nature and collectivist frameworks for technical artefacts: a constructive comparison. *Studies in History and Philosophy of Science*, 42(1):198–205.

Houkes, W. and Vermaas, P. E. (2009). Produced to use: combining two key intuitions on the nature of artefacts. *Techné: Research in Philosophy and Technology*, 13(2):123–136.

Howson, C. and Urbach, P. (2006). *Scientific Reasoning: The Bayesian Approach*. Open Court, 3rd edition.

Johnson, A. (2009). *Hitting the Brakes: Engineering Design and the Production of Knowledge*. Duke University Press.

Koen, B. V. (1988). Toward a definition of the engineering method. *European Journal of Engineering Education*, 13(3):307–315.

Kroes, P. (2002). Design methodology and the nature of technical artefacts. *Design studies*, 23:287–302.

Laymon, R. (1989). Applying idealized scientific theories to engineering. *Synthese*, 81:353–371.

Layton, E. (1971). Mirror-image twins: The communities of science and technology in 19th-century America. *Technology and Culture*, 12(4):562–580.

Levins, R. (1966). The strategy of model building in population biology. *American Scientist*, 54(4):421–431.

MacKenzie, D. (2001). *Mechanizing Proof: Computing, Risk, and Trust*. The MIT Press.

McMullin, E. (1985). Galilean idealization. *Studies In History And Philosophy Of Science*, 16(3):247–273.

Meijers, A., editor (2009). *Philosophy of Technology and Engineering Sciences*, volume 9 of *Handbook of the Philosophy of Science*. Elsevier.

Mitcham, C. and Schatzberg, E. (2009). Defining technology and the engineering sciences. In Meijers (2009), pages 27–63.

Pawley, A. L. (2009). Universalized narratives: Patterns in how faculty members define "engineering". *Journal of Engineering Education*, pages 309–319.

Petrowski, H. (1996). *Invention by Design: How Engineers Get from Thought to Thing*. Harvard University Press.

Polanyi, M. (1958). *Personal Knowledge: Towards a Post-Critical Philosophy*. Routledge.

Popper, K. R. (1959). *The Logic of Scientific Discovery*. Routledge, 3rd edition.

Popper, K. R. (1972). *Objective Knowledge: An Evolutionary Approach*. Oxford University Press.

Popper, K. R. (1974). Replies to my critics. In Schilpp, P. A., editor, *The Philosophy of Karl Popper*, volume II. Open Court.

Popper, K. R. (1977). The worlds 1, 2 and 3. In Popper, K. R. and Eccles, J. C., editors, *The Self and Its Brain: An Argument for Interactionism*, pages 36–50. Routledge.

Popper, K. R. (1978). Three worlds. The Tanner Lecture on Human Values. [Online at http://tannerlectures.utah.edu/_documents/a-to-z/p/popper80.pdf Last accessed 18 Jan 2014].

Rapp, F. (1981). *Analytical Philosophy of Technology*. D. Reidel.

Rittel, H. (1972). On the planning crisis: Systems analysis of the 'first and second generations'. *Bedriftsøkonomen*, 8:390–396.

Rogers, G. F. C. (1983). *The Nature of Engineering*. MacMillan.

Ropohl, G. (1997). Knowledge types in technology. *International Journal of Technology and Design Education*, 7:65–72.

Rushby, J. (2013). Mechanized support for assurance case argumentation. In *Proceedings of the 1st International Workshop on Argument for Agreement and Assurance*. Springer.

Ryle, G. (1945). Knowing how and knowing that. *Proceedings of the Aristotelian Society*, 46:1–16.

Simon, H. A. (1969). *The Sciences of the Artificial*. The MIT Press, 3rd edition.

van de Poel, I. (2010). Philosophy and engineering: Setting the stage. In van de Poel and Goldberg (2010), pages 1–11.

van de Poel, I. and Goldberg, D. E., editors (2010). *Philosophy and Engineering: An Emerging Agenda*, volume 2 of *Philosophy of Engineering and Technology*. Springer.

Vincenti, W. (1990). *What Engineers Know and How They Know It.* John Hopkins University Press.

Weisberg, M. (2007). Three kinds of idealization. *The Journal of Philosophy*, 104(12):639–659.

Wulf, W. A. (2004). Keynote address. In *Emerging Technologies and Ethical Issues in Engineering: Papers from a Workshop*, pages 1–6. The National Academies Press.