TACIT KNOWLEDGE AND ENGINEERING DESIGN

Paul Nightingale

1 INTRODUCTION

In 1752 a French official lamented the slow diffusion of technology from England during the first industrial revolution by noting that "the arts never pass by writing from one country to another, eye and practice alone can train men in these activities" [Harris, 1988, p. 42]. In doing so, he was emphasising the importance of un-codified, person-embodied tacit knowledge to the engineering arts. This short chapter briefly reviews the role of this tacit knowledge in engineering design, highlighting a series of issues of importance to the philosophy of technology. The chapter aims to show how tacit knowledge as a concept is used: firstly, as an empirical description of knowledge that is impossible or difficult to articulate and codify; secondly, to explain phenomena not accounted for in other ways of thinking about engineering design; and, lastly, as a way of thinking about engineering design that is linked to broader and potentially more interesting concepts within the philosophy of technology.

Understanding what tacit knowledge is, and particularly how the concept is used, is important for philosophers of technology because it is now a central concept in policy discussions related to engineering. It is used to explain why knowledge production is localised, cumulative and path-dependent, and therefore why designers, design teams, firms and regions differ in their technological performance. Given the impact of public policy related to the 'knowledge economy' there is a legitimate role for philosophers of technology to investigate the foundations of these ideas in more detail. This is particularly important because the terminology of tacit knowledge is applied very widely, but is rarely explicitly explained [Tsoukas, 2003]. Just what tacit knowledge is, and how it is valuable during the development of technology, is often itself a 'tacit' concept. This is unfortunate, because, as this chapter will argue, while tacit knowledge is a useful empirical descriptor, it is probably too broadly defined to carry the theoretical weight thrust upon it. All the same, the concept usefully points to interesting problems with the dominant conception of technology within modern culture.

The remaining part of this introduction defines engineering, while section two explores what tacit knowledge is and how it is used to explain technological change in the social sciences. Section three proposes an alternative way of thinking about

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tacit knowledge that is argued to be more in tune with its philosophical origins. This is used to explore the process of design. Finally the conclusion points to some of the strengths and weaknesses of the concept of tacit knowledge.

Within this chapter engineering is defined as the art of organising and negotiating the design, production, operation and decommissioning of artefacts, devices, systems and processes that fulfil useful functions by transforming the world to solve recognised problems. This hopefully highlights the practical, creative nature of engineering, with a clear connection to judgements and choices about solutions that achieve a balance between potentially conflicting outcomes in terms of their aesthetic, economic, environmental, technical and other criteria [Tang and Leifer 1988; Schön, 1982; Bucciarelli, 1994]. For an elaborate account of how to define technology and the engineering sciences, see Mitcham and Schatzberg's chapter in Part I of this Volume.

The emphasis on organisation differentiates engineering from other tasks in the production of artefacts [Vincenti, 1990, p.7]. During this production process designing is only one among many roles played by engineers. While design may be one of the most glamorous of engineers' roles, and an emphasis on creativity helps legitimise engineers as professionals, their other tasks remain important even if they are not addressed in this chapter.

This definition is similar to, but slightly more comprehensive than, Dym's in which "Engineering is a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints" [1993, p.17]. It is also similar to G. F. C. Rogers' definition of engineering as "the practice of organising the design and construction of any artefact which transforms the physical world around it to meet some recognised need" (quoted in [Vincenti, 1990, p.5]). Within all three definitions is a shared focus on a temporal process of creating solutions to problems, assessing and selecting them and bringing them to fruition in order that they might effect some change. As such, these definitions reflect academic interests, and may differ from practitioners' perceptions or the reality of engineers' day to day activities identified in ethnographic studies [Jagodizinski *et al.*, 2000].

The specific concern in this chapter is design — widely seen as a central core of engineering practice — which refers to both the content of a set of plans and the process that produced those plans [Vincenti, 1990, p.7]. For Herbert Simon, design simply involves "changing existing situations into preferred ones" [1969, p.111] which blurs the distinction between designing and building a technology. However, the concern in this chapter is specifically with *engineering* design which Ferguson [1977; 1978; 1993] highlights is differentiated from artisan design by its use of drawings that now mediate the previously direct link between the artisan's mind and the materials they are working with.

This introduction of visual diagrams has had profound implications for engineering design and has led to new kinds of visual thinking, new tools, new forms of communication, and a greater division of labour between the people who design and the people who build technology [Ferguson, 1993; Arnheim, 2004]. Once diagrams had opened up a space between designers' minds and their artefacts, many more processes of design became possible. In particular, technology itself could be more easily applied to design to help formulate, analyse, communicate and test designs. As Constant [1980] argues, what distinguishes *modern* engineering from the 15^{th} century engineering of Filippo Brunelleschi is the development of regimes of testing that further intermediate between a designer's mind and the final product. In craft production, improvements in technology occur slowly and in a haphazard fashion, while with modern engineering the specialisation and professionalisation of testing allows a faster, more accurate and much more public comparison of alternatives [Constant, 1980, p.23].

Two changes were vital here: first, the emergence of specialised academic engineering science, such as chemical and electronic engineering, in the early 20^{th} century. These new academic disciplines engaged in research that generated new theories, frameworks, data, tools and particularly a new generation of professionally trained engineers who were able to use new testing technologies [Rosenberg, 1998]. The second important change was the development and widespread use of testing-technology that was often provided as a service by the new engineering consultancies that emerged at the turn of the 20^{th} century. While this might appear at first as a simple Weberian shift from local, tacit knowledge to more global, scientific, visual and articulated technology, the rest of the chapter will argue that such changes have not been so simple.

2 TACIT KNOWLEDGE: FROM THE MARGINS TO THE MAINSTREAM

The notion that tacit knowledge was something more important than just unarticulated elements of conversations appears in the work of the Hungarian doctor and chemist Michael Polanyi (1891–1976). Polanyi moved into the philosophy of science in response to the dominance of positivism, and in particular the potentially totalitarian dangers that he saw in its legitimisation of the centralised control of science. In doing so, he drew on his experience of hands-on experimentation in physical chemistry to argue against conceptions of knowledge that saw it as abstract, mechanical, deterministic and therefore possible to centrally plan.

Instead Polanyi stressed how all knowledge is centred on an agent and her body that is constantly interacting with the world [Polanyi, 1969, p.147]. This interaction, including the use of words and symbols, requires creativity, skill, imagination and personal knowledge. These are essential to our ability to learn through unconscious trial and error when we "feel our way to success" [Polanyi, 1958, p.62]. More importantly, he suggests that our conscious actions are dependent on creative, preconscious processes of integration that produce *new emergent* cognitive phenomena that were not previously present in its components. Consequently, our knowledge is more than the sum of its parts and, while it can be described by rules, it cannot be reduced to rules, with the implication that "we know more than we can say" [Polanyi, 1969; Nisbett and Wilson, 1977].

To explain these ideas Polanyi used an example of the new stereo-image formed by looking at two stereoscopic photographs with different eyes. He argues we become *focally aware* of this stereo-image by being subsidiarily aware of the two separate pictures. Subsidiary awareness functions by bearing on the focus of our attention and making us conscious of merged meanings. Tacit knowing therefore involves a process of integration rather than a [reversible] inference or deduction: it is "knowing a focal object by attending subsidiarily to the clues that bear on it" and this knowledge is lost by focusing on clues in isolation [Polanyi, 1965, p.799]. All aspects of knowing, for Polanyi, share this anti-reductionist character and are based on bodily interactions and creativity.

For Polanyi, this applies as much to tools as it does to ideas and concepts [Polanyi, 1969, p.148; 1968]. While tool-users initially have to focus their attention on their tools, after a period of practice they develop the subsidiary awareness that allows them to use the tools with skill. Focusing on particular features of our experience, such as turning when cycling or on the hammer when hammering, brings them out of subsidiary awareness into focal awareness. This isolates them from our wider tacit understanding and destroys the coherence and meaning of our actions [Polanyi, 1966a, p.10]. This is why focusing on words when speaking, or finger movements when playing the piano, disrupts the flow of these actions [Polanyi, 1969, p.144].

As a consequence, description of comprehensive entities based only on their parts, or on the laws of nature which apply to their parts, can never reveal the operation of the higher principles that define what they are [Polanyi, 1965; 1968]. Polanyi [1965, p.799] argues that:

> to go back to the premises of a tacit inference brings about its reversal. It is not to retrace our steps, but to efface them. Suppose we take out the stereo-pictures from the viewer and look at them with both eyes. All the effects of the integration are cancelled; the two pictures no longer function as clues, their joint meaning has vanished.

Because such tacit knowledge is holistic and non-reducible it cannot be simply built up from components or learnt by following rules [Polanyi, 1966a; 1968]. Polanyi [1966b; 1967; 1969] therefore places great emphasis on what he calls 'indwelling' for comprehension and learning. When we learn, we have to dwell within the concepts we are using for a period of time until they move into subsidiary awareness. This enables us to creatively see the broader coherence of what we are studying and appreciate that body of knowledge as a whole. This can be seen in apprenticeships where students must initially take everything on trust and follow examples until they build up the knowledge needed to understand the activity as a coherent whole. As Polanyi put it:

> An art that cannot be specified in detail cannot be transmitted by prescription, since no prescription for it exists. It can be passed on only by example from master to apprentice. This restricts the range of diffusion to that of personal contacts, and we find accordingly that

> craftsmanship tends to survive in closely circumscribed local settings. [1958, p. 52]

Using more modern terminology, we might say that rules and descriptions of how to perform actions are imposed from the outside, rather than being intrinsic to the actions. As a consequence, they can never fully transmit knowledge without the mediation of a background of cognitive dispositions [Searle, 1995]. As a result, "all knowledge is either tacit or rooted in tacit knowledge. A wholly explicit knowledge is unthinkable" [Polanyi, 1969, p.144].

2.1 Cognitive and social scientists on tacit knowledge

While empirical observations about the difficulty of transmitting some kinds of knowledge may seem trivial, Polanyi argues that they show the implausibility of 'objective' knowledge that is detached from human action and of various theories built on such ideas [Polanyi, 1962; 1969]. Given that explaining how such knowledge is possible has been a central focus of the philosophy of science, Polanyi has had an important, if not always positive, influence on a number of philosophers of science such as Feyerabend, Lakatos, and Agassi. More recently, Searle [1995] has argued that a range of implicit cognitive dispositions, much like tacit knowledge, that he terms the Background provides structure to our thoughts and actions and prevents them from being reducible to rules. Similar ideas have been important in critical attacks on the largely over-inflated claims of proponents of Artificial Intelligence [Dreyfus and Dreyfus, 1986; Collins, 1974; 1990; 2001].

Given how positivist ideas about knowledge have been foundational to many social sciences such as psychology and economics, the concept of tacit knowledge would seem to have the potential to be widely applied [Gill, 2000; Lakoff, 1987]. However, within psychology it is not widely used [Reber, 1989; 1993; Marcel, 1983] and is often considered to be too broad to be analytically useful. It does, however, help explain implicit learning, for example, how experimental subjects learn to anticipate electric shocks without being able to articulate what triggered them and types of knowledge that can only be recalled by doing [Lazarus and McCleary, 1949; Reber, 1989; Underwood, 1996; Lewicki and Czyzewska, 1992; Schacter, 1992].

A considerable amount of empirical work supports Polanyi's view that much of our learning and problem-solving ability is tacit [Sternberg, 1986; Lihlstrom, 1987; Reber, 1989; Dixon, 1971; Merikle, 1992; Berry, 1994; 1997; and Buckner, 1995] as well as his assertions about the roles of cognitive gestalts in structuring perception [Pylyshyn, 1981]. These allow parts of an image to be seen as a whole (as when we recognise a face) even though our eyes only focus on one bit at a time [Reber, 1989].

Recent advances in genetics and neurology seem to support Reber's [1989] conjecture that tacit knowledge is an older, more primitive form of 'knowledge' that supports later evolutionary developments like consciousness and language [Damasio, 1994; 2000]. Much of our cognition is tacit in the sense of not being accessible by the mind, and conscious thought is dependent on neural systems that either cannot be, or are not, part of consciousness. These neural systems generate images of you changing in response to an object, allowing you to feel changes produced by external objects as a subjective, inner, qualitative state [Damasio, 2000]. This seems to fit Polanyi's account — "I shall say that we observe external objects by being subsidiarily aware of the impact they make on our body and of the responses our body makes to them" — very well [1965, p. 805].

Such neural systems allow images to be brought from subsidiary awareness to focal awareness [Posner, 1994] enabling concentrated attention that can be linked to memory and categorisation to allow learning from errors (see Tononi and Edelman, [1999] for a mechanism). Brain imaging technology has shown that as we learn neural images are gradually moved to areas of the brain that cannot be accessed by consciousness. This functional isolation produces a "gain in speed and precision, but a loss in context-sensitivity, accessibility, and flexibility" [Tononi and Edelman, 1998, p. 1847] and makes expert knowledge generated by repeated practice difficult to articulate.

Beyond the cognitive sciences there is also a substantial literature on tacit knowledge that begins to address technology. Again it plays a supporting role for heterodox approaches that contest more positivistic paradigms. For example, tacit knowledge has been a central idea for many years within the heterodox economics literature that places emphasis on technological learning [Nelson and Winter, 1982; Freeman, 1982]. Nelson and Winter [1982, p. 77-79] for example, in a very influential work, highlight the importance of procedural tacit skills in the design and development of technology, and the consequent difficulties involved in creating, diffusing and using technology. In doing so, they build on a body of work by writers on engineering, such as [Constant, 1980, p. 22-27; 2000; Court *et al.*, 1997; Donovan, 1986; Ferguson, 1977; Gille, 1986, p. 1156-61; Stapleton *et al.*, 2005] and [Rogers, 1983] who have reflected on empirical examples of the tacit nature of engineering knowledge, with [Vincenti, 1990] as the seminal work on engineering knowledge.

Because engineering knowledge is partly tacit, it tends to be private [Dosi, 1988, p. 242] and mainly transmitted through face-to-face interaction [Leonard-Barton, 1995; Leonard and Sensiper, 1998]. Its specificity to particular technologies and environments enables firms to develop capabilities that differentiate them from their peers [Pavitt, 1986; 1996; Freeman, 1982; Nelson and Winter, 1982; Pavitt, 1984, p. 343; Dosi *et al.*, 1989; Nelson, 1991; Dosi, 1988, p. 224]. Since these capabilities are associated with improved performance, tacit knowledge is a central focus of the organisational learning literature [Argyris and Schon, 1974; Tsoukas, 1996; Spender, 1995; 1998; Lam, 2000].

Professional organisations, such as engineering design offices, are particularly dependent on the accumulation of tacit knowledge [Becher, 1999; Howells, 1996; Benner, 1984; Eraut, 1999; Megginson, 1996; Veshosky, 1998]. Schön [1982] has highlighted that professional learning involves building up tacit knowledge through critical reflection on actions. This, he argues, makes the practice of design inherently interactive. These ideas have been influential within the management literature, which has sought to understand how tacit knowledge can be built up and used for economic advantage [Teece, 2000; Dougherty, 1992; Leonard-Barton, 1995; Leonard and Sensiper, 1998; Tsoukas, 2003; Brown and Duguid, 2000; Kogut and Zander, 1992]. These ideas have also been applied at the regional and national level within the economic geography literature where the difficulties of transmitting tacit knowledge, and its importance to technological development, are used to explain regional diversity and the geographic clustering of industries [Pavitt, 1996; Asheim and Gertler, 2005; Gertler, 2003; Howells, 2002; Lawson and Lorenz, 1999; Audretsch and Feldman, 1996; Maskell and Malmberg, 1999].

As tacit knowledge became an important concept within economics, management and geography, more critical voices began to emerge that questioned its empirical and theoretical value. Tsoukas [2003] is supportive of the analytical value of tacit knowledge, but suggests that the notion (prominent in the knowledge management literature) that tacit knowledge can be codified misunderstands what tacit knowledge is. As Tsoukas [2003; 416] noted, "tacit and explicit knowledge are not the two ends of a continuum but the two sides of the same coin: even the most explicit kind of knowledge is underlain by tacit knowledge." Breschi and Lissoni [2001] similarly argued that just because tacit knowledge can explain regional agglomeration it does not follow that it is in fact the correct explanation. Cowan *et al.* [2000] expressed extreme scepticism that tacit knowledge was a strong enough concept to explain every deviation from the predictions of neo-classical theory in economics, while Nightingale [2003] likened tacit knowledge to physicists' "dark matter" that explains away the empirical failures of existing theory, but is rarely critically explored.

These criticisms suggest that tacit knowledge has been useful for highlighting the empirical failures of social sciences that build on objectivist conceptions of knowledge, such as neo-classical theory in economics, but the idea itself covers a range of distinct features of cognition that are probably better kept distinct. Even within the literature just reviewed, tacit knowledge covers the embodied nature of knowledge; unconscious knowledge; implicit learning; subsidiary (and focal) knowledge; knowledge that is simply unsaid; knowledge that can never be articulated; and gestalts that structure cognition. Similarly, neurologists distinguish between neural mechanisms; neural mechanisms that produce neural images; neural images that can be potentially brought to conscious attention, i.e. preconscious or potentially conscious mental images; and mental images that are currently being consciously attended to. Being such a broad concept, tacit knowledge has tended to be used as the name for empirical counter-examples to theories of learning or technical change that reduce knowledge to easily transmittable information. This, however, does not exhaust Polanyi's ideas and potentially, as the next section will argue, overlooks a more insightful side of Polanyi's thought.

3 AN ALTERNATIVE VIEW OF TACIT KNOWLEDGE

From the perspective in this chapter on engineering design, tacit knowledge is interesting because Polanyi suggests it is a component of technology, rather than just a kind of knowledge needed to create technology. In much of the social science literature just reviewed, technology and tacit knowledge are distinct and one (tacit knowledge) plays a role in the development of the other. However, for Polanyi tacit knowledge is *part* of technology in the sense that the function of a technology (which is what a technology is) is realised through a process of tacit inference and, like a stereoscopic image, ceases to be what it is in the absence of tacit knowledge. Being a technology is an imposed rather than intrinsic property [Searle, 1995].

Polanyi writes [1958, p. 52] in a quote picked up by Nelson and Winter [1982, p. 119] that "even in modern industries the indefinable knowledge is still an essential part of technology. I have myself watched in Hungary a new, imported machine for blowing electric lamp bulbs, the exact counterpart of which was operating successfully in Germany, failing for a whole year to produce a single flawless bulb." In this quote Polanyi says that indefinable knowledge is "an essential part of technology" rather than "is needed to get technology to work".

While we must be cautious of taking phrases out of context, seeing tacit knowledge as part of technology, in the strong ontological sense that tacit knowledge makes technologies what they are, fits with Polanyi's non-reductionist view of the world and his emphasis on creativity. This is more than the weak epistemological sense in which tacit instrumental knowledge is just needed to get technologies to function. As a chemist Polanyi understood the inherent implausibility of reductionism [1965; 1968], more recently, see [Dupré, 1993]. For chemists, reductionism is misleading because many qualities exist within chemistry that cannot be reduced to, let alone explained by, the behaviour of their component parts. This is why you cannot explain why Gold (the metal) is gold (the colour) or why mercury is a liquid using only quantum mechanics [Scerri and McIntyre, 1997; Dupré, 1993]. Such emergent phenomena do not contradict the laws of nature [Barrow, 1988], but exist within Polanyi's [1965] "boundary conditions" of potential behaviour that is consistent with those laws.

Tacit knowledge adds something to artefacts in the ontological sense because in some instances these boundary conditions can be governed from above: the possibilities opened up by the rules of chess, for example, can be controlled by the strategies of the players. Similarly, the laws of mechanics may be controlled by the operational principles of a machine which are imposed by designers and are not reducible to the machine's components. These higher principles make technologies what they are, and are distinct from the lower principles which remain in operation even if the machine is smashed up. This again highlights Polanyi's point that comprehensive entities, in this case technologies, are more than the sum of their parts.

For Polanyi, the property of being a technology, like the property of being a beautiful painting, is not purely intrinsic. It reflects, in part, a coherence the viewer imposes on an object. Just as paintings are more than blobs of paint, so technologies are more than their components. For Polanyi these additional features are created through a process of tacit inference generated by indwelling. The same ideas are used by Polanyi to explain why science is inherently creative: because complex entities cannot be reduced to their parts, scientists have to dwell within their subjects to build up understanding and creatively come up with theories that explain them. With technology, however, designers don't just understand features of the world that cannot be reduced to lower order principles — they actively create those features. They create new solutions to problems through a process of tacit inference and then change the world to impose those solutions on technological artefacts to create new behaviour that is not reducible to its components.

The idea that higher operational principles, imposed by designers, define what technologies are, is similar to ideas presented more recently by Searle [1995], Kroes and Meijers [2006] and Vermaas and Houkes [2003; 2006]. For Searle [1995, p. 19] technologies have an intrinsic physics — that appropriates Polanyi's boundary conditions — and an imposed function that determines how the technology *should* behave (i.e. drugs should cure diseases and umbrellas should keep you dry) — that approximates Polanyi's operational principle. This imposed function is ontologically prior to the intrinsic physics and determines what a technology is [Searle, 1995, p. 19]. This is why a safety valve is still a safety valve with the function of stopping explosions, even if it malfunctions and fails to do so [*ibid*]. Because technical functions are not intrinsic, technologies can have multiple functions — which is why a computer disc can both store data and stop a coffee cup marking the table. However, the range of possible functions of a given technology is constrained, as a technology's physics has to be able to match its imposed function.

If the epistemic idea that tacit knowledge is needed to get technology to work is the first step away from just seeing technology as artefacts and the Searlean idea that imposed functions are ontologically prior to technologies' intrinsic properties is the second step, then Polanyi makes a further much more controversial step. Polanyi suggests that technologies' intrinsic properties come to embody imposed higher order principles that are generated by tacit inference. Presumably for Searle engineers would understand a function and impose it on the world by changing the world until the technology's intrinsic properties matched the desired function. As a simple theory, this has much to recommend it, but from Polanyi's perspective it doesn't address his concerns about reductionism and would work in a world where reductionism was true. For example, in a world where technological artefacts could be reduced to their component parts, knowledge of those components and their interactions would be sufficient to generate a desired function. Polanyi's position is more contentious and suggests that because reductionism doesn't hold, the function of the artefact isn't implicit in the functions of its components. Instead, higher order boundary conditions define the function and have to be creatively developed through a process of tacit inference.

Once the world is changed to match this function, the tacitly created boundary conditions become embodied in the technology. In more Searlean language, the intrinsic properties of the technology are modified to match an imposed function that is not implicit in the intrinsic properties of its components. The technology therefore comes to embody tacitly created boundary conditions. While dollar bills function as money because society accepts the institutional fact of their value [Searle, 1995], technologies embody tacitly created functions in their physical make up. The resulting behaviour, unlike being money, can continue even if society stops believing in it. For example, currencies become worthless when societies stop trusting them, but an unmanned space probe sent out from earth continues to behave in ways that match an imposed function even when it is out of sight. If in millions of years time, long after the earth has been engulfed by the sun, the probe was found by an alien anthropologist, they might decipher something about our culture from its behaviour because part of our culture is embodied in what the thing actually is.

3.1 The difference between science and technology

Polanyi is particularly interesting to those concerned about engineering design because he extends his ideas about tacit knowledge, the imposed nature of functions, and the irreducibility of comprehensive entities to draw out the differences between science and technology. He writes [1958, p. 177]:

> [T]he beauty of an invention differs ... from the beauty of a scientific discovery. Originality is appreciated in both, but in science originality lies in the power of seeing more deeply than others into the nature of things [i.e. the non-reducible emergent order in chemistry that cannot be reduced to physics, yet is not incompatible with it], while in technology it consists in the ingenuity of the artificer in turning known facts to a surprising advantage. The ... technician ... follows the intimations, not of a natural order, but of a possibility for making things work in a new way for an acceptable purpose, and cheaply enough to show a profit. In feeling his way towards new problems, in collecting clues and pondering perspectives, the technologist must keep in mind a whole panorama of advantages and disadvantages which the scientist ignores. He must be keenly susceptible to people's wants and able to assess the price at which they would be prepared to satisfy them. A passionate interest in such momentary constellations is foreign to the scientist, whose eye is fixed on the inner law of nature.

As this passage shows, when it comes to science Polanyi is a realist and for him scientific theories and explanations are meant to be true. However, when it comes to technology, to use anachronistic terminology, Polanyi is much more of a constructivist [Polanyi, 1967; 1969]. This is because technologies are meant to be useful and usefulness reflects inherently subjective, time-dependent assessments of value. As a consequence, the particular trade-offs made during design are entirely alien to his (very purist) view of science. Moreover, they give design a particular cognitive element not found in science that helps distinguish the philosophy of technology from the philosophy of science. Today such a clear cut separation between science and technology overlooks the role of design in experimental sciences, in both the design of experiments and the design of experimental apparatus, and also the increasing role played by scientific knowledge in design processes.

The idea that science and technology are distinct but closely interacting finds support in the work of scholars of technology such as Pavitt [1998] and Layton [1974; 1976] who distinguish technology from science because technical behaviour has to be (1) reliably created, (2) for users, and (3) in the complexity of the outside world, rather than in the atypical purified conditions of the laboratory as a one-off, largely private, and not necessarily reliable phenomenon. This means that engineers (defined as professionals who are held legally responsible for producing products that are 'fit for use') have to understand the environment in which products are used [Parnas, 1999, p. 3]. This differentiates them from scientists and is why engineers focus on what works *reliably* rather than on *new* knowledge, require a *broad* understanding of how their products will be used, and normally rely on a *legal process of accreditation*, based on an established and formalised body of knowledge, to ensure the quality of their work, unlike scientists who need to be *up-to-date* with the latest findings in their field, can be *narrow* in their specialisation and can let *external referees* determine the quality of their work [Layton, 1979, p. 77–78; 1976; Parnas, 1999].

As Pavitt notes [1998, p. 795] this creates important differences between the purposes of science and technology and the nature of the knowledge they generate:

> One of the main purposes of academic research is to produce codified theories and models that explain and predict natural reality. To achieve analytical tractability, this requires simplification and reduction of the number of variables (e.g., 'Under laboratory conditions . . .', 'Other things being equal . . .'). On the other hand, the main purpose of business R&D is to design and develop producible and useful artefacts. These are often complex, involving numerous components, materials, performance constraints and interactions, and are therefore analytically intractable (i.e. theory and formal models are an insufficient guide to, and predictor of, practice). Knowledge is therefore accumulated through trial and error.

These differences, in turn, relate to the nature and location of the knowledge production processes:

> Academic research is mainly basic research; business research is mainly the development and testing of prototypes and pilot plants. Academic institutions dominate in the publication of scientific papers, and business firms in the granting of patents. And despite examples of spectacularly close links between basic research and technology (i.e. biotechnology), basic research builds mainly on basic research (scientific papers cite other scientific papers much more frequently than patents)

> and technology builds mainly on technology (e.g., patents cite other patents much more frequently than scientific papers). [Pavitt, 1998, p. 795]

Polanyi's conceptual framework of a non-reductionist view of nature, an emphasis on tacit inference and creativity in generating both new scientific theories and new technologies, and the corresponding emphasis on in-dwelling, have important implications for understanding engineering design that are much deeper than a simple empirical observation that some knowledge used in engineering cannot be easily articulated. Dividing design processes into understanding problems, formulating solutions and testing, provides a way to explore how some of the existing history and philosophy of technology relates to Polanyi's ideas.

3.2 The process of design: understanding problems and negotiating solutions

Focusing first on framing problems, most design — even for simple technologies — involves very complex and often conflicting demands that have to be negotiated and clarified: a process that has been nicely illuminated within the history and sociology of technology literatures [Nye, 2006; Hughes, 2004]. These multiple and potentially conflicting demands form part of designers' subsidiary awareness and are often unstated. For example, if I was asked to design a hammer, and produced one made from the horn of the last black rhino calf, there is a very real sense in which I did not understand what was intended, even though at an explicit level my response perfectly matches the requirements. More importantly, the unstated background assumptions are not fixed and change as engineers creatively merge conflicting and often open-ended requirements. This often involves understanding the wider impacts of their proposed solutions. Gardiner and Rothwell [1990; Rothwell and Gardiner, 1988] for example, highlight the importance of considering manufacturability in early design, and how sharing components within a family of designs can simplify production and generate economies of scope. Rothwell [1992] found that the ability to consider these factors, while also paying attention to consumers' needs (which may not be the same as what they think they need) is a vital part of successful design-led innovation.

Formulating design problems is therefore open-ended and cannot be reduced to simple rule following [Dym, 2000, p. 17]. It requires the integration of knowledge, as judgements have to be made about which problems to address and what relative weights to give to conflicting demands [Hacker, 1997]. Many of these multiple criteria will typically have to be considered, merged and explored during the design process. The difficulties of sharing tacit understanding of problems and the uncertainties associated with their exploration make design a negotiated *process* rather than a simple creative *event* [Burcarelli, 1994]. Designers will have subsidiary awareness of many of these issues and bring them in and out of focal awareness as they explore different design options and make explicit their concerns to other members of the design team [Henderson, 1999]. This makes design more complex than simply recognising a problem, matching a solution to that problem, and creating that solution.

There is ample empirical evidence that this process involves knowledge that is difficult to articulate [Vincenti, 1990]. However, Polanyi's framework suggests tacit knowledge plays a role in structuring the design process. Because "being a problem" is an imposed rather than intrinsic property, it is understood contextually, which for Polanyi involves a process of tacit inference. For Polanyi, technologies' coherence is understood through "indwelling", as when Vincenti's [1990] aircraft designers had to get into aeroplanes and sit on pilots' laps because they had been unable to understand pilots' experience of stability without experiencing it as a coherent whole. This knowledge was something that could not be reduced to information.

This may help to explain Cross' [2004, p. 432] findings in his review of studies of design choices which show that experienced designers often approach design tasks through 'solution conjectures, rather than through problem analysis'. Rather than working through the problem in great detail to generate a solution, they use their experience to conjecture design solutions that might work and then try them, using the results of their experiments to better understand the problem they are faced with and how potential solutions might address it. In doing so they select particular features of the problem to attend to and identify potential solutions that they wish to explore. This "imposes on the situation a coherence that guides subsequent moves" [Cross, 2004, p. 423]. Because design choices are open-ended, designers have a degree of choice in how problems are framed, and expert designers have been observed to deliberately define problems in difficult and challenging ways [Cross and Clayburn, 1998; Ho, 2001]. Given the inherent uncertainty of design implicit in Polanyi's non-reductionist ontology, and his emphasis on indwelling, it does not seem surprising that expert designers might proceed in this solution-led trial and error way. Or rather, it would be surprising if they only approached design through the analysis of problems, as by breaking comprehensive entities into parts, analysis loses the imposed coherence that designers are trying to impose.

3.3 Generating solutions

During their training, engineers pick up an understanding of various design options and a contextual understanding of when and where tried and tested solutions can be applied [Nightingale, 1998]. Despite substantial investments, these choices have not been reduced to technical rule-following. Partly, this is because engineers rely on what Vincenti [1990] calls Fundamental Design Concepts that sit in the back of designers' minds and are implicit in their design choices. The first of these are *operational principles* that show how the components of a design will "fulfil their special function in combining to an overall operation which achieves the purpose of the device" [Vincenti, 1990, p. 208; Polanyi, 1958, p. 328]. A classic example of such an operational principle would be Sir George Cayley's definition of the operational principle of an aeroplane involving making "a surface support a given weight by the application of power to the resistance of air" [Vincenti, 1990, p. 9]. Once designers have this idea in the back of their mind they no longer have to consider creating aircraft that flap their wings.

Polanyi argued that these operational principles define what technologies are and exist outside scientific knowledge. As a result, "the complete [scientific] knowledge of a machine as an object tells us nothing about it as a machine" [Polanyi, 1958, p. 330]. This is supported by Vincenti who notes that operational principles "originate outside the body of scientific knowledge and come into being to serve innately technological purposes. The laws of physics may be used to analyze such things as airfoils, propellers and rivets once their operational principles have been devised, and they may even help in devising it; they in no way, however, contain or by themselves imply the principle" [1990, p. 209].

Scientific knowledge can explain why a particular solution produces the result it does, but, because imposed functions are linked to the intentional plans of technologies' designers, scientific knowledge that is divorced or unconnected to these plans will not provide those solutions [Nightingale, 1998]. Vermaas and Houkes [2006, p. 16] make a similar point when they highlight how "technological functions ... create a conceptual bridge between the intentional and structural natures of artefacts; function ascriptions connect the intentional description of the use plan [what the technology will do] with a physical description of the artefacts themselves via the physical capacities of the artefacts that explain why this plan is effective". When scientific theories are used to understand technology they can help explain why a particular design produces the effects it is intended to. However, they cannot explain why those particular effects were intended in the first place.

Vincenti's [1990] second fundamental design concept is the *normal configuration* of a device which refers to the general arrangement of components that allows artefacts to generate their operational principle [1990, p. 209, 102–110]. Car designers, for example, will be able to draw on a paradigm case of a car with four wheels, a front-mounted, water-cooled, petrol-driven engine, and four doors [Vincenti, 1990, p. 209]. Again, such concepts are implicit and rarely articulated during design.

These fundamental design concepts define the structure and direction of the problem-solving process by addressing certain key problems, while leaving a penumbra of flexibility to address the wide variety of other design issues that arise. In doing so, their application re-defines the design problem and makes it more specific, setting up the conditions for the next round of design. The iterative application of operational principles can therefore generate a hierarchy of structurally related, increasingly specific sub-problems that form the basis for the design process [Nightingale, 1998; 2000]. Vincenti [1990, p. 9] nicely highlights this process in which design moves from very general problem definition that translates ill-defined problems into more concrete technical problems, after which the process shifts to overall design which provides an overarching layout of the system, then moves to the design of major components, which is then followed by further subdivision of the project (see also [Bucciarelli, 1994]).

3.4 Testing and modification

Analysis and testing are important in modern engineering design because operational principles only provide rough guidance, and mark the first step in a long trial and error journey to construct a predictable final product. As Dupré [2001, p. 171] notes of internal combustion engines, a first approximation of the operational principle is that:

> a mixture of air and petrol is exploded in a cylinder, pushing a piston down the cylinder; the cylinder is connected to a shaft which is rotated by the moving piston. A number of similar cylinders are connected to this shaft, and a sequence of explosions keeps the shaft rotating continuously . . . But if, on the basis of this explanation, someone lined up some coffee cans partially filled with petrol on the kitchen floor, stuck toilet plungers in the cans, tied the ends of the plungers to a broomstick, and then posted lighted matches through the holes in the sides of the coffee cans, they would certainly not have built an internal combustion engine.

Initial designs are therefore only potential solutions and as Constant [1980; 2000] has argued the mediation of regimes of testing, based around widely-used testing technologies, has transformed engineering and the ability of designers to produce complex technology. A considerable amount of modern engineering design involves working out criteria and specifications that help define how a technological system will achieve its desired function in more detail. The production of specifications involves translating very "general, qualitative goals for the device into specific, quantitative goals couched in concrete technical terms" [Vincenti, 1990, p. 211]. Typically this is a complex process involving the production of diagrams, models, mock-ups and back of the envelope calculations. These artefacts allow knowledge to be shared between the various actors involved in design, and the negotiation (or not) of conflicts within the inherent trade-offs between different design choices. As such, the model or mock-up acts as a 'boundary object' [Henderson, 1998; 1999] to allow shared understanding of the design and design process. This helps mediate between different groups' understanding of the design, and the validity of the 'facts' that make it up.

Such models also play a key role in facilitating learning during design. The complexity of many engineered artefacts, together with their interactions with a changing environment, make working out the effects of many design changes either analytically intractable or analytically very difficult [Pavitt, 1984; Nightingale, 2004]. It is therefore misleading to see design as a simple linear process, particularly with multi-component systems where the appropriate design of one component is sensitive to the design of others. These interdependencies mitigate against trying to change many components at once [Nelson, 1982, p. 463]. Consequently, the design, development and production of complex artefacts involves learning, experimentation, testing, and numerous modification and feed-back loops.

Henderson [1995; 1998; 1999] has shown in a series of wonderful case studies how sketches and models are used interactively at both the individual and group levels "to work out and negotiate various perspectives and to draw in, literally and figuratively, a wealth of tacit knowledge" [1998, p. 141]. Component designers, for example, can show production engineers their designs, who can in turn then articulate their 'gut feelings' why particular parts might be hard to machine, and what design changes might improve them, without having to articulate exactly why. D'Adderio [2001] similarly reflects on the very visual nature of the knowledge used in these negotiations, and the way graphical tools are used by designers to communicate with one another. While Henderson's sociological approach focuses on social groups, her Actor Network Theory approach is consistent with seeing these models as part of a negotiation with nature, in which nature refuses to negotiate on designs that do not work. As a consequence, a lot of engineering design work involves finding out what behaviour nature finds acceptable.

While it is possible to rely on purely empirical methods and unguided changes to produce improvements to designs, such approaches tend to be costly and time-consuming. Instead, design is guided by tacit understanding and rules of thumb that are specific to local situations and technological configurations [Vincenti, 1990]. Given the complexity of most designs, the experimental processes involved in engineering design typically involve creating simplified (i.e. artificially predictable) conditions where the assumptions underpinning these local explanations are true [Nightingale, 2004]. This allows explanations that are too simple to work in the real world to be used to guide the design process.

As knowledge is accumulated, the simplifying conditions can be relaxed and the design process can proceed from 'laboratory conditions' to models, prototypes, field tests and eventually real-world applications. This guidance (hopefully) reduces the number of experimental dead-ends and improves final designs. As this process proceeds, designers take practical considerations, such as the clearance needed for maintenance, or the idiosyncrasies of the staff that will eventually operate the technology, into account. Much of this practical knowledge is unarticulated, context-dependent and defies codification, making testing prototypes an essential part of design [Vincenti, 1990]. In carrying out this testing and modification, designers rely on shared, but unarticulated, ways of thinking and implicit models and analogies. These analogies and models — for example, thinking about the stability of an aircraft about its vertical axis as a 'weathercock' — are again not always easily expressible in words. They often involve a very visual form of thinking, and need to be articulated on diagrams and drawings to be worked on and transmitted [Vincenti, 1990; Henderson, 2000].

Such models are analysed to produce descriptive information about how the design will behave as well as prescriptive data about what is needed for the design to achieve its desired function. Academic and industrial engineering research has developed a series of theories, theoretical tools, mathematical methods and intellectual concepts for analysing designs. Like Polanyi's operational principles, some of these intellectual tools are specific to engineering, for example, concepts like propulsive efficiency and feedback enable quantitative analysis, but are not scientific terms [Mayr, 1976, p. 882; Vincenti, 1990, p. 216; Ferguson, 1978, p. 450]. Such tools allow engineers to investigate how well designs and design options match, or mismatch, design criteria and specifications.

During the process of testing artefacts and components, engineers switch between seeing technologies in functional terms as part of a wider system of use, and seeing them in terms of their intrinsic physics which can be subject to empirical analysis. In each instance, the alternative is left implicit and the new knowledge generated through testing integrated back into the process of design. Designers therefore have to reflect on their designs and the results of tests, negotiate changes to inter-dependent components, and work out prescriptive performance criteria, often using models and diagrams as tools for what Hutchins [1995] has called "external cognition", that are modified in an attempt to capture implicit, background understanding and tacit knowledge [Henderson, 1995].

The role played by tacit knowledge in Polanyi's thought contrasts with a strong tradition of understanding engineering design in terms of a means-ends practical reason. Simon [1969], for example, is an influential exponent of the view that design is a "science of the artificial" in which decomposable problems are analysed and fitted back together. For Polanyi design can't be about taking problems apart and fitting them back together again because coherent entities cannot be reduced to the sum of their parts. Instead, as Schön [1982] has shown, it is inherently creative and involves interactions, practice and reflection on actions.

For Polanyi, design can't only be about adapting means to well-defined ends because those ends and means are not always at hand. They will often have to be created, and this creative process involves tacit inference. Seeing design as a clean "science of the artificial" often misses the inherently creative, messy and open-ended processes of developing and adjudicating between conflicting demands and benefits. The tacit nature of the knowledge involved in creating the novel boundary conditions that make technologies behave in particular ways cannot be reduced to a simple calculation. Reducing design to a science of design leaves un-explored the complex, creative processes used by designers, and the role of diagrams, models and visual thinking in exploring design options.

4 CONCLUSION AND SYNTHESIS

This chapter has hopefully shown that tacit knowledge is a useful, but probably over-encompassing, concept that nevertheless helps illuminate important features of engineering design. While most of the literature that uses the concept of tacit knowledge does little more than report that there are features of engineers' knowledge that are difficult, if not impossible, to articulate, this chapter has highlighted that Polanyi's original ideas are substantially more interesting. Polanyi begins with an ontology that rejects reductionism and asserts that many entities are more than the sum of their parts. This, he implies, has implications for how we understand the world, as coherent entities cannot be understood by understanding their components; hence Polanyi's insistence that we know more than we can tell. Instead, Polanyi stresses the importance of tacit inference for perceiving coherence. Learning, therefore, often requires a process of indwelling that builds up knowledge and gradually moves it into subsidiary awareness to enable tacit inference to take place.

Polanyi extends these ideas beyond science to the design of technology to highlight how scientific knowledge does not encompass the entirety of what can be known. Because designed technology has a coherence beyond its component parts, the design and production of technologies involves knowledge that is distinct from scientific understanding of those components. Scientific understanding, for Polanyi, focuses on truth, but technological knowledge instead focuses on usefulness. As such, it reflects inherently social concerns about practical applications and judgements about the inherent trade-offs that must be made during design. Operational principles, that imply how a technology will achieve its function, are inherently technological. Their selection and application closes down the number of possible alternative design routes and focuses the design process in a particular direction. In doing so, their selection structures the design process by making the design problem more specific.

For Polanyi, tacit knowledge is therefore an essential feature of design and is what allows designers to creatively generate new solutions. It helps explain the creative nature of design, the limited success of attempts to automate design (and weaknesses with the outputs of AI more generally), the importance of diagrams and visual knowledge, and why good design practice is so hard to learn, articulate and teach.

In applying Polanyi's ideas to design, it is difficult to avoid the feeling that tacit knowledge is too broad a concept for the theoretical burdens that have been imposed on it. The cognitive sciences have broken tacit knowledge into a series of distinct, but interacting, phenomena. Similarly, Vincenti and other historians of technology have tended to use more precise and more applicable concepts like operational principles, engineering research, implicit knowledge, etc. While these concepts often draw heavily on Polanyi's original ideas, they allow a deeper exploration of design. For example, they help us understand how flexible Polanyi's operational principles are, and how much additional testing has to be undertaken to move from ideas in designer's minds to final, working artefacts [Vincenti, 1990].

Much of this more recent work, particularly by authors such as Bucciarelli and Henderson, also adopts a much more social understanding of design than the often very individualistic approach taken by Polanyi. While Polanyi's philosophy of science often presents a historically misleading picture of the heroic lone scientist, his philosophy of technology similarly too often presents design as something that occurs within one person's head. The ability of tacit knowledge to explain a host of very diverse phenomena, which on closer inspection actually turn out to involve something else, suggests a substantial weakness in how the concept is used. For example, tacit knowledge might explain the localised nature of design capabilities, or localisation might be the result of specialised designers simply having to interact more often with one another. Too often the fact that tacit knowledge might explain a phenomenon is used to draw the incorrect inference that it provides the correct explanation.

There is no doubt that the concept of tacit knowledge provides useful ways of thinking about design, particularly empirically important aspects of design that are often overlooked elsewhere (visual knowledge, for example). All the same, more work needs to be done towards clarifying what tacit knowledge is and how or if it plays a role in design.

Such a conclusion is open to two substantial criticisms. On the one hand, it allows the concept of tacit knowledge to get away with too much. To anyone trained within the Anglo-Saxon analytical tradition, Polanyi's ideas can be difficult to follow as he jumps between different meanings of the term tacit knowledge. Too often, one gets the feeling that difficult problems are being explained away, rather than explained. Concepts like tacit knowledge, tacit inference and indwelling are rarely clearly defined and it is often difficult to see what they do, and, more importantly, what they do not, encompass. Polanyi might respond that he is correct and many of the problems that seem to exist are simply metaphysical hangovers from assuming that reductionism is true and knowledge is a 'mirror of nature', to use Rorty's phrase. Admittedly, if one thought that all entities in the universe were reducible to the sum of their parts then Polanyi's ideas may seem magical or mysterious, but he knows as a scientist that the universe isn't like that. He is therefore simply explaining empirical events. Such a response would seem to be provided with substantial empirical support by historians of technology: much engineering knowledge is difficult to articulate, codified information is rarely sufficient to generate technology, many design concepts are implicit and much of the knowledge used in design involves interaction with material objects, such as drawings, and reflection upon their changed meaning.

On the other hand, an alternative critique might be that this chapter has not gone far enough. In trying to explain tacit knowledge *and* engineering design the chapter has dissolved, and therefore lost, the inherent interconnections between the two. The two have to be understood together, through a process of tacit inference, in order to be understood at all. Like the stereoscopic images, by bringing each into focal awareness the coherence that links them has been lost. Such a criticism should not be dismissed too easily, as intellectual figures as diverse as Raymond Aron and Charles Taylor have found Polanyi's ideas extremely profound. In response, hopefully this chapter at least hints at this possibility; however, a full integration is beyond the capabilities of the author and the length constraints of an introductory chapter.

To reach a conclusion that would placate both sides does not seem easy. There do seem to be good grounds for scepticism about the value of the concept of tacit knowledge. Where it is used, it tends to be used to explain empirical phenomena that are not explained within existing frameworks in the social sciences. However, the explanations often don't seem particularly robust. Rather than providing a way to change or radically reformulate existing ways of thinking about technical change, economics or design, tacit knowledge seems to plug the gaps in existing theories and allow them to proceed onwards unchallenged. Rarely, if ever, are questions raised about the deeper compatibility between the resulting theoretical chimeras [Tsoukas, 2003].

All the same, tacit knowledge as a concept does hint at something more substantial. It was put forward by Polanyi as part of a very radical attempt to challenge the foundations of 20^{th} century social thought. Hopefully, this chapter has shown that, rather than reinforcing existing ways of thinking, Polanyi's ideas can help understand their very real limitations. By highlighting the emergent nature of phenomena it stresses the unpredictable nature of the world we inhabit, and the failures of reductionism and strong determinism. Polanyi's ideas can be used to attack the legitimisation of 'scientism' without being anti-science [Gill, 2000]. By showing that technological phenomena cannot be reduced to scientific phenomena, even if they can be explained by science, tacit knowledge as a concept can help to highlight the distinct nature of the philosophy of technology [Vincenti, 1990]. Given the ever-increasing importance of technology to society, this suggests a continuing and growing importance for the philosophy of technology in helping society understand what technology is, how it generates unintended consequences, and how it can be directed along more fruitful paths. Polanyi's ideas may raise more questions than they answer for the philosophy of technology, but those questions are important enough to deserve more time than they have received so far.

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