What is Technology? Six Definitions and Two Pathologies

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Aims

This paper aims to integrate recent philosophy, history, sociology and economics of technology (Vincenti, 1990; Searle, 1995, 2001; Dupre, 1993; Houkes, 2009; 2006; de Vries, 2003; Nye, 2006; Rosenberg, 1976, 1990; Pavitt, 1987, 1999; Meijers, 2009) to explore six definitions of technology and two pathologies. It aims to clarify the relationship between different ways of understanding technology, and provide a preliminary overview of their relative strengths and weaknesses.

Introduction

Despite providing the taken-for-granted infrastructure that supports our daily lives (Hughes, 2004), the amount of academic work on what technology 'is', and what gives it its power and influence, is relatively limited (Mitchem and Schatzberg, 2009). However, across a range of disciplines there is an increasing recognition that technology can't be understood as applied science and the amount of research on technology is increasing in both scale and sophistication. Unfortunately, because it comes from different academic disciplines the research remains rather fragmented, reflecting different positions, perspectives, interests and settings: technology is sometimes understood in terms of artefacts, sometimes in terms of knowledge, and sometimes as solidified social relations, etc. This has resulted in a lack of commnication and generated a degree of confusion. To explore how these different perspectives relate to one another, (and hence their relative strengths and weaknesses), the paper explains their underlying assumptions. To do this it starts with four empirical features of technology. First, the term technology is new, and much newer than many people think. Second, its meaning has changed through time. Third, technology is not applied science as they have different aims and outcomes. Fourth, technological knowledge has an inherently tacit element.

The paper then explores theoretical features of technology, using a Continental approach of exploring contradictions in the content of concepts drawing on empirical and historical examples. These problems are then resolved within an increasingly abstract hierarchical structure,[1] to generate a typology of perspectives on technology. The results are triangulated using a traditional Anglo-Saxon Analytic approach (type-content; process-outcome). For ease of understanding different perspectives are named after different professions (i.e. an engineer's perspective, a sociologist's perspective etc.,). This naming is for illustration purposes and should not be taken to imply any strong claims about overlap or imply exclusivity or identity. The discussion and

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[1] That goes from the individual, to the particular and then universal.

conclusion explore how these different ways of thinking about technology interact and can generate pathologies in how technology can be understood.

Empirical features

1 The Recent Appearance of Technology

We start with the first point: technology is a recent word that appeared in the lexicon much later than most people realise (Mitchem and Schatzberg, 2009; Hughes, 2005; Nye, 2006). We can roughly date the emergence of the term "technology" to the 17th century. It appeared in the second edition of Thomas Blount's *Glossographia*, a 1661 dictionary of "Hard Words", but was not in the first edition (Nye, 2006), so we can assume it started to be more commonly used around that time. However, it wasn't in common usage. Nearly a century later it wasn't in Samuel Johnson's dictionary of 1755, nor in subsequent editions until the mid 19th century. In fact the term technology was rarely used in the 19th century . Cornell's 'Making of America' archive contains 100,000 19th century documents. Technology was found in it only 34 times before 1840. Of those 34, 31 were in a single book *The Elements of Technology* by Bigelow (1829), who dropped the term from the 1840 edition, which he retitled *The Usefulness of Arts* (Mitcham and Schatzberg, 2012: 35). Between 1860 and 1870 'technology' only appeared 149 times in the archive while the term invention appeared 24,957 times (Nye, 2006: 12).[2]

It was still a specialist term in the early 20th century. It got its first mention in the *Encyclopaedia Britannica* in the 11th edition (1910-11), where it was noted as an acceptable alternative to 'technical' in an article on Technical Education (Nye, 2009). It only became a common term in the latter half of the 20th century and did not have a major entry in the *Encyclopaedia Britannica* until the 15th edition which came out in 1974, some four years after man had walked on the moon (ibid).

2 The changing meaning of technology

The second empiricla feature about technology is that during this period its meaning changed: Technology used to mean a classification system for the arts or systematic study of an art i.e. an *-ology* of *techne* (Nye, 2006). Blount's *Glossographia* defined it as '*a treating or description of Crafts, Arts or Workmanship*'. It mainly refered to a treatise on the practical arts, or a technical description, such as a book on the "technology of glassmaking" (Nye 2006:15).[3] Its use gradually became more abstract and it started to be applied to the skills, machines and systems studied at a technical university (ibid). When the Massachusetts Institute of Technology was founded in 1861 its name was considered odd, reflecting this new use of the term (Mitcham and Schatzberg, 2012: 37).

One reason it was rarely used in the 19th century was because people used the German term *Technics* was used to refer to 'the totality of tools, machines, systems and

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[2] Even Karl Marx, who is often thought of as a technological determinist, only used the term sparingly. It does not appear in the *Communist Manifesto* and he waited until 1860 to introduce the term in *Capital* initially in a footnote, where he intriguingly notes:

> *Technology discloses man's mode of dealing with Nature, the process of production by which he sustains his life, and thereby also lays bare the mode of formation of his social relations, and the mental conceptions that flow from them* (1906:406n2).

Arnold Toynbee's 1880-1 lectures that coined the phrase "the industrial revolution" similarly avoided using the term.

[3] This meaning can be seen in how the word combines the Greek root *techne* (an art or skill) and the suffix *ology*, from logos, which is usually translated as a branch of learning, knowledge or science. *Techne* shares a common root with *texere* to weave and *tegere* to cover, that in turn draw on the Sanskrit *tekhn* which has association with carpentry (Mitcham and Schatzberg, 2012: 32). *Techne* therefore already incorporated a notion of practical knowledge, so the addition of *logos* added a second order knowledge about knowledge meaning.

processes used in the practical arts and engineering' (Nye, 2006:12) while *technique* was used to describe the knowledge associated with the industrial arts.[4] Technology began to displace *technics* about 100 years ago as writers in the United States such as Thorsten Veblen championed the term. By the middle of the twentieth century this meaning had reached popular usage, and technology displaced *technics* as the term for complex systems of industrial products, devices, processes, skills, networks of production, transportation and communication and the knowledge required to make and use them (Mitcham and Schatzberg, 2010: 39; Nye, 2006:15).

3 Technology is not Applied Science

The third empirical feature is that technology is not applied science. The problem with treating technology as applied science is that there are plenty of instances where technology appeared before the science that explains it. The Wright brothers were flying before aerodynamics was developed and steam engines were in widespread operation before thermodynamics. Technology can appear before science because scientific understanding is not needed to develop technology. After all, it is possible to know how to produce an effect without knowing how an effect is produced.[5] For most of history technologies were developed without any inputs from institutionalised or professionalised science, and the notion that technology is applied science was only emerged in the late 19th and early 20th century when it was deliberately propagated by engineers as they sought to professionalise and appropriate some of the prestige of the scientific community for themselves (Kline, 1995; Layton, 1979; 1971).

Rather than technology being applied science, science and technology are more usefully understood as distinct bodies of knowledge, practice, material things and institutions that interact with one another, but are often independent (de Solla Price, 1965).[6] Their interactions are complex with new technologies providing science with tools for investigation and the development of technology often providing science with problems to solve. Radio astronomy and modern oceanography are examples of sciences that emerged directly from an advance in technology (radio telescopes) or have been fundamentally transformed by one (military sonar) (Rosenberg, 1994). Solid-state physics, on the other hand, emerged after the construction of the transistor and its expansion was driven by the need to explain phenomena emerging in industrial applications (ibid). Hence science often operates just behind the technological frontier, with basic research in post-War UK, Germany and Japan lagging, rather than leading, relative performance in technical change (Pavitt, 1999, p. 235).

This reflects science and technology having different purposes, with science (and academic research) aiming to produce models and theories that explain nature (and sometimes allow predictions of its behaviour), while technology is developed to generate useful artefacts. Technologies need to function reliably, for a wide range of users in the messy, dynamic complexity of the outside world (Pavitt, 1987; Rosenberg and Steinmeuller, 2013). As a result, engineers, as professionals held legally responsible for ensuring products are 'fit for use', require a broad understanding of how their products will be used in their operational environment (Parnas, 1999, p. 3). They focus on what works reliably rather than what is new, and because the costs of failure are typically high, they normally rely on a legal process of accreditation, based on

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[4] As late as the 1950s, when historians of technology were deciding what to name their professional association, there was a debate about calling the society the history of technics as the term technology was so novel (Hughes, 2005:3). Lewis Mumford was still using the German term *technics* in the subtitle of his book on *The Myth of the Machine* in 1968.

[5] For example, Xenon, an inert gas, was used as a general anaesthetic in the 1950s, at a time when medical scientists didn't understand what consciousness is, how it is maintained or how it is removed, and chemists had no idea Xenon was capable of having any chemistry at all. As an inert gas it was, unsurprisingly, considered inert. It wasn't until 50 years later than these began to be understood.

[6] Derek de Solla Price's (1965) metaphor of two dancing partners who have come closer together through history captures the idea nicely.

an established and formalised body of knowledge, to ensure the quality of their work (ibid).

With science, on the other hand, the ability to explain natural phenomenon requires the phenomena to be analytically tractable. This typically requires a degree of simplification to reduce the number of variables and interactions under consideration (Pavitt, 1999). To focus on the phenomena of interest, experimental scientists intervene to create artificially simplified laboratory conditions that protect the phenomena they are studying from the messy complexity of the outside world. Unlike technologies that are sold to the public, scientific experiments only need to work in purified environments, as a one-off, largely private, and not necessarily reliable phenomenon. Scientists, unlike technologists, need to be up-to date with the latest findings in their field and focus on what is new, (rather than what is robustly established), can be extremely narrow in their specialisation and let external referees determine the quality of their work (Layton, 1979, pp. 77–78; 1974; Parnas, 1999).

4 The Tacit Nature of Technology Knowledge

The fourth empirical feature of technology is that it draws heavily on tacit knowledge (Polanyi, 1966a), the collective term for the largely unconscious, unarticulated knowledge that provide the basis for actions and the context for conscious mental states (see Nightingale, 2003 for a review). This knowledge is socially embedded in our complex material cultures and reflects the skillful, creative ways people negotiate and adapt within it. The nuanced understanding that enables these social interactions is physically embodied in the neurobiological systems of peoples' brains and bodies, that may not be accessible to consciousness, making it difficult to articulate and transfer.

This tacit background of predispositions and memories, created by our interactions with our material and social environment, provides the structured context needed to consciously understanding things. Formulating and understanding explanations, for example, requires a framework of taken-for-granted assumptions that aren't unarticulated. Geologists take for granted that rocks didn't come into existence 5 minutes previously, and do not feel the need to acknowledge this (Taylor, 2012:13).

All knowledge is therefore partly tacit, but technical knowledge has a particularly strong tacit component (Polanyi, 1968). This is partly because technologies are mind dependent objects whose purposes reflect the subjective aims of actors, and whose operation depends on implicit, unarticulated knowledge (Searle, 1999). Using a tool depends on a sophisticated ability to conceive of alternative, counterfactual futures and possibilities, which, in turn, depends on a background sense of time as a process that moves from remembered past actions to projected future impacts (Nye, 2006).

The complexity of technology is reflected in the depth of this background knowledge, which is why the term *technical* is associated with both 'being difficult to understand' and being 'associated with technology'. As a result, developing complex technologies requires technology-specific, accumulated expertise,[7] that takes time to acquire, can be difficult to articulate, is typically passed on by face-to-face mentoring, and is learnt through practical, hands-on manipulation of artefacts, prototypes, and models (Vincenti, 1990). As the next sections will show there are further reasons why tacit knowledge is so important to technology, but discussing them requires a little theoretical background.

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[7] When aeronautical engineers needed to understand the desired level of instability that pilots sought (planes that are too stable or unstable are difficult to fly), they had to sit on pilots laps to get a sense of it, as this was more effective than attempting to get the pilots to articulate it (Vincenti, 1990).

Theory: The Nature of Technology

The empirical features of technology, that differentiate it from science, reflect their different purposes. These different purposes parallel deeper differences that are understood in the philosophy of science in terms of differences in 'Speech Act' structures. Both science and technology depend on people being able to have conscious mental states about the world. This *aboutness* relationship between mental states and the world is referred to as intentionality. Intentional mental states can be categorised by their type (i.e. fear, hope, belief, etc.) and by their content (i.e. 'it will rain') (Searle, 1969). Some also have conditions of satisfaction (Austin, 1975). For example, beliefs are true or false, and desires are fulfilled or not fulfilled (Searle, 1969).

Conditions of satisfaction can be categorised in terms of their direction of fit, which can be either mind-to-world, or world-to-mind depending on the whether the intentional mental state or the world is changed (Searle, 1969). For example, the belief 'it is raining outside' has a mind-to-world direction of fit, because the mind has to match the world for the belief to be true. If it is sunny outside the belief has to change to match the world in order to be true. On the other hand, my desire for a cold drink has the alternative world-to-mind direction of fit, because the world has to change to match the desire, by me actually getting a cold drink, if the desire is to be fulfilled (Searle, 1969).

The different purposes of science and technology are reflected in different directions of fit. Simplifying again with the intention of developing a more realistic account later, with science ideas and explanations are adapted to match the world, while with technology the world is modifed and adapted until it matches an idea, typically expressed in the form of a design (Searle, 1995, p. 19). Science is associated with a search for reliable knowledge about nature and sincerely expressed scientific theories, explanations and statements are meant to be true (and match how things are in the world). When theories, statements and explanations are false (i.e. don't match how things are in the world), scientists attempt to adapt them until they match the evidence.

Technologies, on the other hand, have a different purpose and are meant to generate functions. They either function or malfunction depending on how their real world behaviour matches our preconceived ideas about how they should behave. When we create them, or when we repair them after they malfunction, we change the world to match our ideas about their desired behaviours.

This difference has a number of implications. Since only speech acts that are adapted to match the world can be true, only scientific statements, but never technologies, are true or false (Searle, 1998).

It is also why there is a difference between the inherently social, subjective and time-dependent nature of technologies' imposed functions (which are value-laden ideas about how technologies should appropriately behave), and the asocial, objective and timeless nature of scientific facts (Nightingale, 2004). The truth of scientific statements about the mass of an electron depends on facts that are entirely independent of what people say or think and should therefore hold for all people, and for all times. While a Manolo Blahnik kitten-heel is arguably more appropriately worn by Nastassja Kinski attending the Oscars, than by Silvio Berlusconi addressing the Italian Parliament (Nightingale, 2004). In this case the appropriateness of a particular piece of footwear is dependent on how well it performs its imposed function which, in turn, is based on sophisticated, value-laden understanding of the appropriateness of it within a particular historical, cultural social setting (ibid). As a result, technical knowledge tends to have a more subjective element and be more context, person and time-dependent.

Lastly, the difference in direction-of-fit is why scientific statements, like all statements can be about the past, while technological designs, which have the same direction of fit as desires are (like desires) always forward looking. You can make a scientific statement and have a theory about the begining of the universe but you can only design something for the future (ibid).

5 Thinking about Technology

These distinctions lead to an initial way of thinking about technology in terms of artificial functions, first as entities that generates desired outcomes:

> Definition 1: technologies are entities that produce artificial functions.

And second as an outcome of a future orientated problem-solving *process* that reflects technologies desire-like speech act structure:

> Definition 2: Technologies are entities produced by a problem solving process that changes and transforms the world so that it matches a pre-conceived idea, or plan, or design to generate a desired artificial function.

The first of these definitions might be termed an engineer's perspective reflecing how newly qualified engineers see technologies as things that solve the problems they are set. While the second might be termed an innovation or technology management perspective reflecting managers' interests in improving the process. In both cases the name is intended as an illustration rather than an identity.

The entities that are generated by this process are typically artefacts, but can be intangible, like software or organisational procedures or rules. 'Artificial' refers to the human created, intended nature of technologies and the 'function' refers to the uses to which we put things. Cars are for driving, drugs are for changing biochemical processes, and screwdrivers exist to exert torque on screws. So a heart functions to pump blood but isn't a technology because it isn't man made, while garbage is man-made but isn't a technology because it is an unintended outcome rather than an intended function.

The philosopher John Searle, whose terminology we are using here, highlights that functions are observer relative and imposed rather than intrinsic features of the world (see also Meijers, 2009). Intrinsic things, like planets, mountains and molecules, exist independently of people and would exist even if there were no people around. Imposed features of the world, on the other hand, only exist relative to the intentionality (i.e. the aboutness of mental states) of observers or users (Searle, 1995 pg. 6). So an object can have properties like being made of wood and metal that are intrinsic, but is only a screwdriver because someone created it as a screwdriver, uses it as a screwdriver, or regards it as a screwdriver (ibid). This property adds an epistemologically objective feature to the object even if it doesn't add anything material.

These ideas imply a conception of technological artefacts in two parts (Searle, 1995; Meijers, 2009). The first functional element reflects our understanding of how the technology *should* behave. The second captures its intrinsic physical properties that determine how it *will* behave. For example, drugs should cure diseases and umbrellas should keep you dry in the rain and their intrinsic physics will determine how well they work.

Importantly, the imposed function, rather than the intrinsic physics, determines what a technology is. As Searle (1995, p. 19) notes, a safety valve is still a safety valve with the function of stopping explosions, even if it malfunctions and fails to do so. Since imposed functions define what technologies are, at least part of what technology is exists in our minds, suggesting it would be useful to move from seeing technology as artefacts to seeing it as a complex of artefacts and knowledge.[8]

Doing so helps explain the normative quality inherent in technology. Assigning a function positions the entity in relation to a teleological framework, whose end results

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[8] Nathan Rosenberg, for example, understands technology as knowledge, but divides knowledge into embodied and disembodied knowledge, with embodied knowledge corresponding to technical artefacts that are mind dependent objects, built to solve problems using specifically technological understanding.

is positioned within a system of values that allow us to make normative judgements about how well technologies achieve their imposed functions. This is why we can judge a stone a better or worse paperweight (imposed function), but not a better or worse stone (intrinsic property) (Searle, 1995, page 15; see also Vermaas and Hourkes, 2006). Such normative frameworks form part of the taken-for-granted, tacit, background knowledge used to understand technology.

Because functions aren't intrinsic, technologies are 'multiply realisable' with many technical choices available to fulfil a given function and many functional uses possible for a particular form. A computer disc can function to store data or it can function to stop a hot coffee cup marking the table, or function to stop a table wobbling by being placed under a short leg (Nightingale, 1998). An artefact's actual function typically depends on an associated technique or body of practice. This can change over time, allowing the same artefact to be used to generate different functions. Since this technological knowledge typically depends on other artefacts, which in turn rely on other bodies of knowledge, technologies often require a wider social and physical environment of complementary devices, systems, institutions, rules and norms to operate. Collectively these make up the technology's technological regime. This leads to a third way of defining technology that is often used by sociologists concerned with how structural features of the regime (beyond the innovation process) influence outcomes (Hopkins, 2004; Blume, 1992; van Lente, 1993):

> Definition 3: Technologies are comprised of artefacts, that generate artificial functions, techniques and the wider institutional regime required for them to operate.

Thinking about technology in terms of a central core and gradually diffusing surroundings highlights the difficultly of putting a clean boundary around technology. This is particularly the case if what looks like static social-structures are actually dynamic processes where technological artefacts, understanding, and their environments co-evolve.[9] Consequently, technical change isn't just a one way process of changing the world to match an idea, or something determined by static social structures. Instead it is generated by a distributed, often contested, co-evolutionary process that involves incremental improvements and radically new combinations, in which understanding and artefacts both change in a complex combination of deliberate design and unintended outcomes.

This suggests the previous ways of thinking about technology can be potentially misleading if an inappropriately short period of time has been captured. Hence a fourth way of defining technology, similar to historians' longer-term view of technical change such as Moykr (1990), is implied:

> Definition 4: Technology is the outcome of a distributed co-evolutionary process in which functions, knowledge, artefacts and their environment, mutually adapt to each other.

To move from understanding technology as the outcome of a process in time, to understanding it in historical time, we need to dig a little deeper and go from looking at the differences of type to explore why those types differ.

Theory II: The Direction Argument

Because science and technology have different purposes, they move between causes and effects in different directions (Nightingale, 1998). As a first approximation, with science, the aim is to understand the world and the underlying laws of nature that

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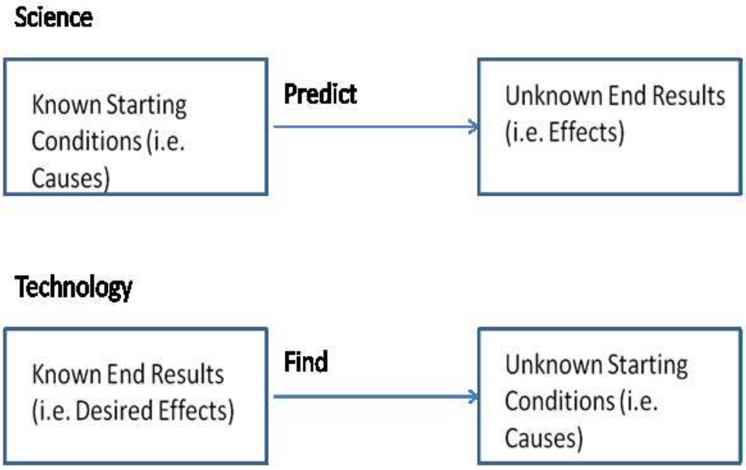
[9] This coevolution allows reasonably stable configurations to diffuse in ways that are largely autonomous from static-structural constraints. The diffusion of dot.com mania, for example, did not occur because all of a sudden the world was structurally similar to Silicon Valley.

drive its behaviour (Barrow, 1988; Ziman, 2000). Knowing these laws enables scientists to explain how known starting conditions (causes) will generate an unknown end result (effect). For example, if you know the mass of a cannon ball, the angle and direction a cannon is pointed in and the energy in the charge, the laws of physics allow you to make a good prediction about where the cannon ball will land and the trajectory it will follow through the air.

With technology, on the other hand, and again as an initial approximation, technologists are trying to achieve a particular outcome, and hence know the desired end result, or effect, they are looking for (Nightingale, 1997). However, at the start of the design or innovation process they do not know which particular configuration of components (starting conditions) will generate that desired effect (end result). With technology, the desired outcome (or effects) are known, while the starting conditions (or causes) that will generate that end result are initially unknown. For science it is the other way around - causes (starting conditions) are known and used to predict and understand unknown effects (end results).



6 Generating Unknown End Results with Scientific Explanations

Strictly speaking, the abilty of scientific knowledge to generate unknown end results from known starting conditions only occurs for a small subset of situations. Even when scientific knowledge comes in the form of laws, their ability to predict may be severly constrained. They are most successful when they take the form of differential equations, which are algorithms for defining future states of the world from present conditions (Barrow, 1988:279). The algorithmic structure incorporates the symmetry conditions (or constant relations, or invariences) that define the law of nature.[10] To predict outcomes the algorithm also needs a starting state or initial condition, and various constants of nature. If the symmetry conditions hold strongly, the initial starting state is precisely defined, nothing external interferes, and errors propagate in a linear way, then the behaviour predicted by the differential equation should match the behaviour in the real-world reasonably well. Unfortunately, outside of precisely control experimental settings that have been specifically designed to create artificial conditions where external influences don't interfere, this rarely holds (Dupre, 2001; Cartwright, 1983). Even in experiments deviations occur because of (1) symmetry breaking between the laws of nature and their outcomes, and (2) non-linear error growth (Barrow, 1988; Nightingale, 1998).

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[10] We do not observe these laws of nature directly, but instead observe their outcomes and abstract back to the laws of nature. For example we observe a ball falling back to earth and abstract the laws of gravity from that behaviour.

In general the symmetries of the laws of nature are conserved between the law and its outcome. Sometimes however, this conserved symmetry may be unstable (Ruelle, 1991, p. 40). For example, a series of laws of nature may end up generating a pencil perfectly balanced on its point, conserving the symmetry between the laws of nature and its outcome. But this symmetry between the end result and the underlying laws of nature are unstable as any deviation, down to quantum fluctuations, will cause the pencil to fall, breaking the symmetry between the laws and their outcomes (Barrow, 1988, p. 210, Barrow, 1995, p. 50). Since the original laws of nature do not contain any information about the direction in which the pencil fell they cannot predict it (Barrow, 1988).

This symmetry breaking is a fundamental feature of the universe and is how the simple laws of physics can interact to produce such a complex universe full of emergent properties that are qualitatively different from the underlying laws of nature (Barrow, 1998; 1995). This complexity is consistent with the laws of nature but cannot be reduced to them as extra historical information about symmetry breaking is needed to fully describe and explain it. Hence, prediction requires not just starting conditions but also (empirical) historical information.

The problems of prediction are made worse by non-linear error growth, that occurs when small errors in initial conditions lead to larger errors later on, the so called Butterfly effect (Stewart, 1989; Ruelle, 1991). For example if one was simulating 'the Laplacian billiard ball universe' every time a ball impacted with another the difference in angle between the real world and the simulations would double. So after only ten impacts it would be impossible to say where on the table the ball would be, even if the centres initially differed by only a micron per second (Ruelle, 1991 p. 42). Symmetry breaking and non-linear error growth mean that very similar starting conditions, and in some instances the same starting conditions, can lead to very different outcomes. This can severely limit the predictive power of scientific theories and allows commonplace, micro-level unpredictability to influence macro-level outcomes (Nightingale, 1998).

Together symmetry breaking and non-linear error growth imply that 'theory is a weak guide to practice' when generating and testing technology (Pavitt, 1999). While the *ex post* performance of a technology will be consistent with the laws of nature, *ex ante* scientific theories will be insufficient to predict the behaviour of complex artefacts. Modern technologies involve too many interacting components, materials, and performance constraints to make them analytically tractable (Pavitt, 1999). Technical change therefore largely involves the empirical discovery of "grubby and pedestrian" facts. It is not concerned 'with the general and universal, but with the specifics and particular' details that can have a major influence on outcomes (Rosenberg, 1976 p. 78; Rosenberg and Steinmeuller, 2013). The problems caused by a missing comma in a piece of software controlling a nuclear power plant, for example, illustrate how small initial errors can lead to large differences in outcomes because of symmetry breaking, and hence why technologists are interested in details rather than generalities.

7 Generating Unknown Starting Conditions with Operational Principles

As the previous section highlights, science can't necessarily directly provide the answer to the questions that technologists are interested in (ibid) - namely, what set of intially unknown starting conditions will generate a known desired outcome? This is because there is no unique scientific answer to that question: a wide range of designs (starting conditions) can generate a desired outcome. Choosing between them involves subjective judgements. Furthermore because technological functions are imposed rather than intrinsic, they do not imply anything much about how they can be generated (i.e. which set of starting conditions will generate the desired function) (Polanyi, 1968; 1966b; Vincenti, 1990). Since there isn't a one-to-one relatinship between outcomes and starting conditions, and symmetry breaking means laws of nature can't be 'reversed' to find solutions to technical problems, science can't provide the answer. Instead, technology is produced by making value infused choices about the operational principles that define the basic way in which the technology works.

Operational principles have the form 'phenomena x can be generated using y' and provide an uncertain suggestion about which set of starting conditions might generate the desired end results.[11] For example, Sir George Cayley (1809) defined the operational principle of fixed wing aircraft as making 'a surface support a given weight by the application of power to the resistance of air'. Operational principles are to engineers what theories are to scientists, but they 'originate outside the body of scientific knowledge and come into being to serve some innately technological purpose' (Vincenti 1990, 209). They are typically chosen by extrapolating previously successful examples, based on the assumption that 'similar problems will have similar solutions' and experience of what counts as similarity in that particular context (Nightingale, 1998).

The application of an operational principle of the form 'behaviour x can be produced by y' immediately generates a new, more specific, sub-problem about how to produce the y that generates the desired behaviour x (See Nightingale, 2000a & b). This sub-problem (*how to generate y*) can be solved by a new operational principle, which in turn generates a new sub-problem to solve. As a result, the repeated application of operational principles generates a hierarchy of increasingly specific, interacting problems and proposed solutions through a process of what engineers call 'functional decomposition'. The resulting inter-related problem solving tasks will be structured in the order which they can be completed because the outputs to some problem solving tasks will be inputs to others (i.e. z will have to be produced before y, and y before x etc). The technical term for a series of problem-solving tasks that are structured in time and generate a technology is an innovation process (ibid).

The choice of operational principles at the top of the hierarchy, at the level of project definition and conceptual design, reflect social choices and value judgements about how to best proceed, structured by a shared, but often contested, normative system of values (Vincenti, 1990). Technological infrastructure, for example, typically embodies non-market public values about issues such as universal access etc, with technologies reaching out to all citizens equally (Constant, 1984). Further down the hierarchy, problem-solving is less political and is largely reduced to addressing technical problems defined by previous decisions made higher up the hierarchy (Vincenti, 1990). Similarly, radical innovations involve new and often very different operational principles at the top of the hierarchy that have major disrupting effects that redefine large parts of the hierarchy and require new solutions. Incremental changes, on the other hand, are generally lower down the hierarchy and are less disruptive (Constant, 1980; 2002; Vincenti, 1990).

8 Tacit Knowledge and Inferring Operational Principles

The abilty of technologists to use operational principles to generate outcomes consistent with, but not implied by, or reducible to, scientific laws of nature, raises questions about how they do it. To answer this we need to move away from seeing tacit technical knowledge as a static background of dispositions that gives meaning to perceptions, and instead see it as an active dynamic process by which technologies' functions are creatively inferred.

Michael Polanyi is normally understood to have suggested technology draws on tacit knowledge because all knowledge draws on on background knowledge. While this may be true, it is a misleading account of his ideas. Polanyi was instead proposing

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[11] Their original definition from Polanyi was how a technology's parts "fulfil their special function in combining to an overall operation which achieves the purpose of the" technology (1958, p. 328)

a more fundamental reason for the importance of tacit knowledge. Polanyi was a chemist, and chemistry is a science that explores how configurations of atoms generate novel emergent properties in the final molecules that typically cannot be reduced to the properties of the component atoms. For example, you cannot explain why Gold (the metal) is gold (the colour) or why mercury is a liquid only using quantum mechanics (Scerri and McIntyre, 1997) even though all these phenomena are consistent with quantum mechanics.

Chemists' ability to understand phenomena that can't be reduced to physics, is an example of a more general capability to understand emergent properties. Polanyi explains this by making a distinction between being *focally aware* of something, where it is the focus of our attention and being *subsidiarily aware* of something, where we are conscious of it, but not paying attention to it. Polanyi uses an example of the new stereo-image formed by looking at two stereoscopic photographs with different eyes, to show how we become focally aware of this stereo-image by being subsidiarily aware of the two separate pictures. By being conscious of, but not focused on, the individual photos, we can become conscious of a stereoimage through a process of mental integration. Focusing on particular features of our experience brings them out of subsidiary awareness, which isolates them from our wider tacit understanding and destroys their coherence (Polanyi, 1966a:10).[12]

Polanyi argues we gain new understanding when repeated exposure to something (what Polanyi calls indwelling) moves our knowledge of it from conscious attention to tacit, subsidiary awareness.[13] Once there, the mental images held in subsidiary awareness can be integrated, which allows us to see the broader coherence of the subject of our knowledge (Polanyi, 1969:148; 1968; See Damasio 2000 for its neurological basis).

This is a process of creative integration rather than a (reversible) inference or deduction,[14] which is why focusing on words when speaking, or finger movements when playing the piano, disrupts the flow of these actions (Polanyi, 1969:144). This creative integration means our knowledge is more than the sum of its parts, and while it can be described by rules, it cannot be reduced to rules, or learnt in its entirety from rules (1969).

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*' (1958:52).

This ability to '*know more than we can say*' allows scientists to understand emergent properties and allows designers create new functions that exploit emergent properties that are not implied by, or reducible to, the laws of physics. In the example of the pencil perfectly balanced on its point, this symmetry breaking was driven by gravity. With technology, on the other hand, symmetry breaking is artificially created, by designers building up understanding and integrating it to create a 'sense of similarity' that is imaginatively extrapolated to a counterfactual future setting to create something new. This is why tacit knowledge is so important to innovation. It is active integration not just passive context.

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[12] Similarly, the Jaskow rabbit picture that can be seen as either a rabbit or a duck, allows us to switch between focal and subsidiary awareness at will by choosing how we see a particular image.

[13] When tool-users first start they 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. In apprenticeships students follow examples until they build up the knowledge needed to understand the activity as a coherent whole.

[14] It is 'knowing a focal object by attending subsidiarily to the clues that bear on it' (Polanyi, 1965:799).

9 Redesign Cycles: Exploring and Testing Operational Principles

Because operational principles are based on a tacit sense of similarity they are inherently fallible and uncertain. They are therefore only the first step in a costly and time-consuming process of trial and error experimentation that is needed to generate a final outcome (see Dupre, 2001: 171-2).[15] Once the application of operational principles generates a configuration of components, they will need to enter a cycle of testing, redesign and modification where various dead-ends are explored to discover operational principles that generate the desired function.

9.1 Moving Up, Down and Around the Hierarchy

As noted previously, the development of complex technologies typically involves a strategy of functional decomposition, that reduces complexity by dividing the delivery of functions into components (Nelson, 1982). These components solve particular design sub-problems and feed into the delivery of the overall function. Because the outputs of some components/problem solving tasks provide inputs to others, failure in the design of one component can have implications for the design of other components in the system (ibid). This creates the potential for redesign feedback loops (when design failures cause operational principles higher up the hierarchy to change) and in extreme cases redesign explosions, where the entire design process has to be restarted.[16]

Hence there can be considerable variance in the number of redesign cycles and movement up, down and across the hierarchy. These additional redesign cycles all contribute towards the time and cost of development projects and can act as barriers to technical change. This, in turn, creates potential opportunities for firms that can acquire the ability to reduce this variance, and move from their initial design to the final design faster and at less cost than their rivals. For example, a firm proposing an initial perfect design that would passes all its tests and go straight into production without any redesign, would be more effective than a firm proposing a design that repeatedly fails tests and sets designers off along a failing trajectory.[17]

A key design decision therefore relates to how innovative, and hence how far from known, established designs, the initial design will be. This choice trades off the potential added value of an innovative design against the increase uncertainty (and additional redesign cycles involved). With systemic techologies, design processes can be improved through better choices about the architecture of the product and the design process. This often requires better understanding of the order in which tasks need to be undertaken, to avoid sub-component interactions that cause redesign cascades. These redesign cascades can be further reduced through improved comunications and co-ordination that ensures design criteria for different components are up to date

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[15] As John Dupre (2001, p. 171) notes, a first approximation of the operational principle of an internal combustion engines 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.'

[16] The number of the redesign cycles, and hence the time, cost and risk of a development project, is contingent on a) the number of components and problem-solving tasks, b) how inter-dependent the sub-tasks and components are, c) whether the technology is "fragile" and requires substantive redesign following even minor changes, d) whether new operational principles need to be discovered, e) whether customer requirements are clear and unchanging, and f) whether the external environment changes as the result of the introduction of the technology (Nightingale et al 2012).

[17] Creating a better match between an initial and final design is like a control problem that involves creating a match between an imagined, desired behavior and the world (and so is subject to innovations in accuracy, speed, reliabiliy and scope (Nightingale et al 2003)), but is more complicated because the final outcome can be largely unknown at the start of the process.

and reflect modifications in related components. These managerial behaviours all compress the time and cost needed to design, test, modify and produce a product (Nightingale et al 2013).

9.2 Engineering: Moving Around Redesign Cycles on Paper

Once the scope of innovation and the architecture of the product and its design process are defined, design and testing at the component level can also be improved to reduce the number of redesign cycles. This can be done by higher quality, more predictable design that better matches the desired function (through better understanding of how components will behave), and by faster, more accure testing, (through more effective learning).[18]

The simplest form of design would involve inductively assuming 'similar problems have similar solutions' and proposing and testing a design without knowing what causes its behaviour. Many European Cathedrals were built using this form of *artisan production* where design, production and testing are integrated. When buildings fell down, builders would start again, repeating the process until they stayed up. Artisan production used passive 'testing as validation' to discovers if operational principles work, but because it is atheoretical, it offered little guidence about what to do if the technology being tested failed. Under such conditions innovation was slow and relied on passing on the lessons of experience in the form of tacitly understanding and rules of thumb.

The shift from artisan production, to *engineering* seperated out design, which was now done on paper, from testing and building. This division of labour increased dexterity, speed and encouraged the introduction of new technology, such as paper-based designs and plans that mediate between engineers' ideas and the artefacts they build (Constant, 1980).

One reason why this is important is because engineering knowledge is very visual (Ferguson, 1977). Engineers need to understand three dimensional relationships. When desinging a technology, its final performance will be generated by complex webs of causal interactions in which the outputs of one process/component provide the starting conditions for the next. All of these interactions are potentially subject to symmetry breaking and non-linear relationships, and so are difficult to predict from scientific theories. Because these causal interactions typically require proximity to generate functional outcomes, artefacts normally need to have a particular shape and be placed in a particular way in physical space in relation to other devices to function. So while all the positions in 3D space will be consistent with the laws of physics, only a few will generate the desired behaviour. While these can't be directly deduced from fundamental scientific theory they exists as facts to be discovered, that can be understood, explored and inductively extrapolated.

Visual representations allow the selection of operational principles to be guided by tacit understanding of technologies' normal configurations in 3D space.[19] Visual representations provide an external way for technologies, or rather representations of technology that emphasise key features of interest, to be kept in subsidiary awareness. This provides focused context for design activity and enables engineers to exploit what Hutchins (1995) calls 'external cognition' (see also, Henderson, 1998; Fergusson, 1977; 1993).[20] By allowing representations of artefacts, rather than the artefacts themselves,

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[18] Here the distinctions between being inductively predictable based on empirical regularities, being predictable because explainable and being explainable by not predictable is useful. As noted earlier, one can know how to produce an effect without knowing how an effect is produced.

[19] The selection of operational principles during this process is assisted by engineers' background knowledge of 'normal configurations' that reflect "the general shape and arrangement that are commonly agreed to best embody the operational principle" and how the different components will fit together (Vincenti, 1990, pp. 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 (ibid).

[20] Indeed, one reason software technologies fail so often is because the causal interactions they depend on are so much harder for engineers to visualise, put down on paper and communicate than

to be analysed, tested, compared and communicated they reduce the risk and cost, while increasing the speed and effectivness, of design. Symbolic representations help designers articulate operational principles, allow off-line analysis, improve internal and external communication, and allow ideas to be publicly displayed and critiqued before expensive artefacts have been produced.

9.3 Modern Engineering - Moving Between Experimental Models

The use of paper based designs seperated out design from building and testing, and differentiates artisan production from engineering. *Modern engineering* is different again because it involves the use of models (epecially working scale models) to further seperate testing and building. This reduces the costs and risks of testing and allows'systematic parameter variation' to map behaviour and potentially understand its underlying causes (Vincenti, 1990:138; Rosenberg and Steinmeuller, 2012:1139; see also Mokyr, 2002: 68-76).[21] So rather than passively testing if something works, or gathering empirical data on performance models allow active 'testing as experimental intervention' (Yaqub and Nightingale, 2012; Hacking, 1983) by intervening in the world to create something new in order to understand how and why it works.[22]

This is valuable because there are an infinite number of possible explanations for any test results, suggesting learning from tests would be impossible. However, only a finite number of explanations are actually at hand. Tacit knowledge and scientific understanding help interpret results and select a smaller sub-set of explanations that are reasonable to pursue, reducing the number of dead-ends that need to be explored before a useful outcome is found. Experiments can reduce the sub-set of explanations further by creating purified conditions where only a subpopulation of competing explanations' assumptions hold (e.g. constant temperature, no light or oxygen, etc.).[23] Tests can be done to exclude others. The results of these tests and experiments also provide additional new information to inform positive hypotheses about where to look. Models similarly allow a smaller subset of assumptions in different explanations to be focused on and explored.

Learning is difficult if the number of possible explanations is too large to select from at reasonable cost, or the simplified experimental conditions are too unrealistic to learn from. This can be addressed by building up understanding using simplified models and then gradually relaxing simplifying assumptions to make them more realistic (Yaqub and Nightingale, 2013). This moves testing through a series of experimental stepping stones from laboratory experiments to full scale working prototypes. Drug discovery, for example, uses standardised 'model organisms' that trade-off ease of learning (simplicity) against clinical relevance (complexity). Drug discovery might therefore move from yeast, through nematode worms, to zebra fish, mice and monkeys, before human trials begin. In each setting, learning is possible if the key properties of interest in the models are similar to those in the subject being modelled. When these conditions hold, models allow the extrapolation of as yet unobserved properties from the model to the thing being modelled because their common properties share chains of cause and effect (provided they are not influenced by dis-analogies) (Morgan, 2012; La-Follette and Shanks 1996:112; Ankeny, 2001).[24]

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the causal interactions found in mechanical artefacts.

[21] This was introduced to engineering in 1759 by John Smeaton (who used it in a study of the performance of waterwheels and windmill).

[22] Models therefore provided the basis for the development of new engineering sciences, and transformed the production of engineered systems in the late 19th century as new testing machinery was developed, and a new industry of testing and analysis services was born.

[23] Experiments involve instrumental intervention (Hacking, 1983) involving varied, measured and controlled manipulation of experimental conditions (Nelson, 2008) to isolate and test specific mechanisms, so the divergent implications of competing explanations to be compared (Nightingale, 2004).

[24] To warrant expectations of unobserved properties (i.e. to justify taking the predictions of the model to be true) relies on the model embedding a "good argument" that is valid (the premises imply the conclusions) and sound (the premises are trustworthy, i.e. major premises are constructed from

Under such conditions models can be used as cognitive tools "for inquring into and reasoning with" (Morgan, 2013) or what Callon (2008) calls 'calculative prosthetics' (see also, Baird, 2004). Importantly, because they are tools they are capable of having multiple functions. Models can act as (1) *cameras* that capture causal relationships and connections, and allow effects to be visualised and better understood (Morgan, 2013); (2) *communication* tools, that allow the representation of designs and ideas in ways that allow tacit understanding to be diffused around a design team (Bandura, 1986). This is related to their role in (3) *co-ordination* where they help integrate design activity by acting as objects that anchor representitions of tasks and allow them to be managed. Models can be used for (4) *calculating* behaviour and outcomes, and hence be used to explore changes (Morgan, 2012). This allows their use in generating (5) *credibility* about which future options are most realistic. Lastly, models can be integrated into the final technology and act as (6) *control* systems, where they are used to co-ordinate the final system (Nightingale et al 2003). Models, and hence modern engineering, are only possible if the model being investigated, in a weak sense, reflects the reality of the technology that will be built. This requires material conditions to be in place that allow science and technology to coincide (in the sense of fitting together rather than mirroring). These conditions were not in place for most of history, and the next-but-one section discusses why they emerged when they did.

9.4 Technical Change as a Persistent Process

Before exploring this, it is worth moting some implication for how we think about technical change. The shift from artisan production to engineering and modern engineering seperates out the process of technical change from production. As a result, technical change, with all its cycles of proposing and testing operational principles, can continue after products are launched and is potentially very open ended. Technologies are often very primitive when they are first developed, and it can take a long time to work through all the redesign cycles and develop them into a commercially viable form (Rosenberg, 1976). The original computer, for example, required 15,000 valves and was extremely unreliable (ibid). While products can be launched when they are better than others on the market, the process of technical change can, and normally does, carry on, often over long periods of time. New operational principles are explored at various levels of the hierarchy and the product, process or service is incrementally improved (with models speeding up this process and reducing its costs and risk).

This suggests that it is misleading to think that technology emerges from innovation processes as concrete finished things, or even as the 'outcome' of a discrete process with a fixed end point. In fact, commercial launch is a rather arbitrary and potentially misleading point to define the shift from invention to finished innovation, as it implies the innovative work has finished and we now move onto diffusion (Rosenberg, 1976). In reality, this sharp distinction between innovation and diffusion doesn't exist, and innovation continues as systems are made to fit together.

Moreover, technologies can be fundamentally transformed by complementary innovations that change or enhance their performance in these systems (Rosenberg, 1976). Natural gas was a waste product until innovations in high pressure piping turned it into a highly valuable product (ibid). These combinations can in turn generate new uses, as was seen with the laser and the compact disc, which in turn can satiate non-obvious "new" needs (ibid).[25]

This suggests it is useful to move from thinking of technology as a fixed thing coming out of a fixed innovation process, to seeing it as something that extends

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sub-premises that have a strong foundation).

[25] It wasn't obvious in 1950 that there was a problem for the Sony walkman to solve. Similarly, Edison's phonograph was originally intended to record the last wishes of dying men, and there was no early intention that it would be used for music. Similarly, the laser, radio, TV, computer and telephone, all originally had fundamentally different functions than they have now (Rosenberg, 1976).

beyond individual devices to other artefacts and develops over long time frames, often distributed over many firms and many seemingly distinct innovation processes.[26] Technologies and products are therefore distinct analytical categories, with products simply capturing technologies at particular points in time.

This leads to a fifth more comprehensive way of defining technology that captures this ongoing process of dynamic modifications in a wider environment. This generates a perspective on technology that can be seen in research on technology governance where the focus is on modifying processes to direct technical change (see, for example, McLeish and Nightingale 2007):

> Definition 5: technology is all the knowledge, concepts, experimental processes, tangible and intangible artefacts and wider socio-technical systems that are required to recognise technical problems and to conceptualise, formulate, research, develop, test, apply, diffuse and maintain effective solutions to those problems as they change through time.

Modern Science and Modern Industry

The focus on process in definition 5 positions technology in time, but not yet in historical time. To do that we need to look at the content of the processes by which science and technology interact. Recall that because theory is a weak guide to practice, most technology development requires extensive experimental cycles of redesign to find operational principles that generate a required function. For most of history scientific understanding only provided limited guidance during this process because science was too simplistic and technology too complex for them to overlap much (Price, 1965). Over time however, they have begun to overlap more, and this interaction has profoundly changed both (Rosenberg, 1966). Science now guides the development of technology, reducing costs (by reducing the number of redesign cycles) and improving performance. Science has similarly changed with technology providing new sites and subjects of investigation and importantly new tools for doing so. The increasing overlap between simple science and complex technology has been driven by five main processes of paricular relevance in understanding technology.

The first of these is simply ongoing improvements in scientific understanding, which have allowed scientists to increasingly understand more complex technological phenomena.[27] The development of the engineering sciences in the early 20th cenutry was a key development. The second process involved new instrumentation and experimental equipment developed in the 19th century, that was used to purify reagents, allowing their chemistry to be more readily analysed. These purification technologies were then scaled up and applied to remove the contaminants from industrial processes that caused their behaviour to deviate from scientific theories that had been developed in laboratory settings, using purified chemicals. So rather than science just becoming more complex to match technology, this second complementary process involved technology becoming simpler, through purification, to match science.

10 Models and Modern Science

The third of these processes combines the other two and involves purification at the theoretical level through the introduction and application of intangible cognitive technologies, such as models and other abstracta, that intermediate between the linguistic descriptions in theories and objects of representation (Turro, 1986; Teller, 2001: 398). This builds on, and mutually supports, the application of increasingly complex physical experimental apparatus to create artificial environments where scientists can

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[26] These time frames can be longer than the life of the firms involved, suggesting it is misleading to associate a particular technology with a given firm: Firms may die, but technologies live on.

[27] This has often been driven by new instrumentation and experimental technologies.

intervene to create new phenomena (Hacking, 1983). Models in science, like all models, are asbstract cognitive tools (technologies), and as such can act as “autonomous agents” (Morrison, 1999) operating in partial independence of theory and evidence (ibid, Turro, 1986).[28]

Models can be defined as abstract or physical objects that are regarded by their users as simplified representations of something (Teller, 2001:397). Being a model is therefore an externally imposed function rather than an intrinsic property. Models can represent aspects of the things they are similar to because those concrete objects have properties and properties are parts of models (ibid, 399). The specifics features of what needs to be explained or predicted then provide the basis for deciding (i) what counts as similar and (ii) what costs are associated with different kinds of error (ibid 401-2).

Models are particularly important to science as they act as abstract experimental apparatus that construct the artificially purified conditions where the 'other things being equal' of *ceteris paribus* laws of nature always hold with prefect precision and accuracy. Hence scientific laws as abstract mathematical structures are, strictly speaking, true *of*, or rather *in*, models rather than the real world (Cartwright, 1983). Newton's first law, for example, applies to objects that are not being acted on by any force. Such objects may exist in Newton's model universe, but do not exist in the real world.

Because scientific theories typically apply in models, they don't mirror nature. Instead they define 'a kind of natural system' that is given empirical content by 'theoretical hypotheses' of the kind 'such and such a real system is a system of the type defined by the theory' (Giere, 1979:69-70; 1985). These theoretical hypotheses provide a connection between models and the world, and allow models to idealise away the problems of application. This allows them to achieve generality (at the price of perfect accuracy and precision), but means real world application requires considerable technical skill to generate results that are good enough for the case at hand (Teller, 2001; Morgan, 2014).

With modern science, that “good enough” can be very good indeed. Models of varying levels of inexact accuracy and precision have been hugely successful in generating knowledge - 'advanced as adequate' to use Teller's term - with further supporting models helping us to understand underlying mechanisms, and the strengths and weaknesses of the core models in particular contexts (Teller, 2001). Together these networks of interconected models have successfully generated unifying accounts of the behaviour of a range of natural and technological systems.

Such systems of interconnected models bring science and technology together by increasing the scope and depth of understanding. They provide abstract ways for making seemingly different things similar (i.e. heat diffussion, gravity and the price of options). They simplifying the things being understood through a process of *ceteris paribus* abstraction which increases the complexity of scientific explanation by outsourcing application to theoretical hypotheses and practical skill. As a result, they improve scientific and technological learning by standardisation and improved communication. This in turn leads to tighter experimental cycles and therefore reductions in the number of experimental dead-ends that are explored (through the provision of additional hypotheses and guidelines from supporting models). Moreover, they provide guides for the design of (experimental) technology that enable it to behave according to theory. For example, the design of the LEP detector at CERN drew on the models developed by particle physicists (Nightingale, 1997).

Even the theories of knowledge used earlier, where truth corresponds directly to reality, unmediated by models, are themselves simplifying models that simplify the reality of science (where theory and evidence are mediated by a model) by removing

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[28] Their introduction, as mathematical models can be seen with Maxwell realisation that Kelvin's inverse square law of heat-flow through a material was structured in the same way as the force of gravity (and today we would add the pricing of options). As a result, despite physical dissimilarities they share the same type of mathematical description.

models to leave the relationship between theory and evidence as a correspondance. This simplification provides for general application at the cost of accuracy and precision, for if strictly applied it would imply all science is false as no theories are perfectly accurate and precise (Teller, 2001).

11 The Division of Labour and Modern Industry

The fourth way science and technology can come together is through the simplification of industrial processes that occurs because of expansions in the division of labour. In lectures in 1748 and 1751 and then in the *Wealth of Nations* Adam Smith (1776, 20) argued that one of the main benefits of the division of labour was that it separated complex tasks into a series of simpler tasks that were regular enough for workers and 'philosophers, or men of speculation' (i.e. scientists) to understand. The idea that the complexity of production technology had to be reduced before it could be scientifically understood and then improved by introducing machinery, was picked up by Charles Babbage (1832) de Tocqueville (1835), Karl Marx (1906) and Veblen (1906). The later two used the idea to differentiate a radical break between traditional manufacturing, which was a simple extension of workshop production where science and technology are distinct, and modern industry where science and technology overlap.

Because traditional manufacturing was based on tools that were manipulated by hand, the design and organisation of production were constrained by the physical characteristics of the workers. With modern industry a different machine logic takes over. The expansion of overseas markets in the 18th century increased the division of labour enough to separate complex production tasks into a series of simpler, separately analysable steps and tasks.

Once the division of labour had simplified tasks, science and technology could be brought together, as these simplified tasks could be replaced by machines. This made production predictable enough for science to be usefully applied to analyse, monitor, continuously improve, reorganise, optimise and control it (Rosenberg, 1966) The complexity of the representations needed to describe production processes could reduce as the underlying tasks became simpler, allowing them to be analysed and used to produce much more complex and systemic production processes (ibid).

The human constraints on production reduced as more machines were introduced. What had previously been groups of free standing, self contained machines separated by tasks undertaken by people, were increasingly understood and co-ordinated as systems. Production went from being organised around people to people being organised around production. In Veblen's words the new system '*compels the adaptation of the workman to his work, rather than the adaptation of the work to the workman*' (Cited in Marx 2010).

Systems' components can be optimised and controlled together, which increases both their interdependencies and performance (Nightingale, 2009). Abstract representations of these inter-dependancies became incorporated into control systems, allowing new production economies of scale, scope, speed and system (Nightingale et al 2003, Chandler, 1990; Beniger, 1989). These changes mark out a shift from machine-based industrialisation to industrialisation characterised by socio-technical systems: the shift from the steam engine of the first industrial revolution to the railways of the second (Chandler, 1977). In addition to free standing machinery (steam locomotives) these systems involved (1) ancillary equipment (stations, yards, viaducts, signal systems), (2) capital intensive corporate business organisations, (3) specialised technical knowledge (engineering and telegraphy), (4) specially trained workforces, (5) institutional changes (standardized track gauges and standardized national time zones), (6) the use of formal scientific knowledge (Marx 2010, 568) and as Ruth Odenzeil (2006) highlights (7) a gendering of the technology, with work that had previously been open to women, now associated with power, science, rationality and control, and largely restricted to men. Moreover, (8) these changes generated substantial improvements in technological leverage and productivity, that (9) resulted in changes in the social distribution of risks and rewards, that in turn (10) resulted in changes in how technologies and firms were regulated and (11) the institutional architectures used to socialise the risks of industrialisation (i.e. the New Deal, the Second Bill of Rights).

None of the words that were current at the time could capture these changes or how the new systemic, diffused, decentralised power of these systems was helping shift the United States from a rural, primarily agricultural nation to the urbanised, economic and military superpower of the next century. A novel term "technology" was introduced that underwent a shift in meaning. Technology no longer meant a science of the practical arts (the *–ology* of *techne*), because the practical arts were no longer arts, based on craft. They had been transformed (by technology) in a way that allowed science to replace art and create something fundamentally new. As Marx put it:

> "Modern Industry rent the veil that concealed from men their own social process of production, and that turned the various spontaneously divided branches of production into so many riddles¸ not only to outsiders, but even to the initiated. The principle which it pursed, of resolving each process into its constituent movements, without regard to their possible execution by the hand of man, *created a new modern science of technology.* The varied, apparently unconnected, and petrified forms of industrial processes now resolved themselves into so many conscious and systematic applications of natural science to the attainment of given useful effects." (1867/1906;504, emphasis added).

The vagueness of the term 'technology' allowed it to capture the complex combinations of artefacts, systems, forms of knowledge, and activities that made up modern industry (Marx, 1997:981).[29] This suggests a sixth historically informed way of defining technology associated with historians of technical change (a broader subject than the history of technology) like Nathan Rosenberg (1968), Nick von Tunzelmann (1995), or Ed Constant (1980) interested in what drives the changing economic importance of science:

> Definition 6: technology covers the artefacts, systems, knowledge and activities associated with the development, production and use of artificial functions that have been developed *after* the conditions were in place for science and industrial production to converge and production to move from machinery to systems.

12 System Leverage: Momentum and Lock in

This definition is valuable because it helps highlights how science and technology changed after they mutually adapted themselves to one another. Craft-based, people-centric production was replaced by rationalised, scientific, continuously improving, system-focus production. Science changed as it adapted. The older distinction between science *representing* the fabric of reality, and science *intervening* in the world to create artificial experimental conditions (Hacking, 1975), now starts to become fuzzy.

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[29] As Oldenziel notes 'the ascendancy of technology as a keyword in the United States neatly parallels the emergence of America as a superpower committed to technology as a the key tool for development in the rest of the world' (2006). In Europe, on the other hand, the new term 'technology' captured the destructive power of the First World War where modern mass production, advanced manufacturing, chemistry, logistics and control where applied to the mass killing of Europeans for the first time (Mitcham and Schatzberg, 2009, 47). The slaughter in the trenches was caused by something more than isolated artefacts and was different from the massacres inflicted by artillery and machine guns during the wars of colonial expansion in the late 19th century. It was the result of the integration of military artefacts into two co-ordinated systems which once set against one another took on a horrifyingly destructive life of their own. A new term was needed for this new phenomena to capture its diffused power and moral emptiness.

Science is no longer 'natural science' because the subject of science is no longer exclusively nature. Science is now applied to a new form of production that transcends the limits of people and enhances our capacity to direct energy, create leverage and disrupt previously stable systems. Categories of interest are not only defined by nature but also by the extent they relate to bottlenecks on systems' growth and performance, and their consequences, risks and impact on humans and the environment. Science took on a greater role supporting the new regulatory frameworks that emerged in responses to the changes discussed in the previous section.

Technology also changed. Engineering-science models feed directly into systems' control (Nightingale et al 2003; Hughes, 2005).[30] Components coevolved together, enabling and constraining each other, with components that constrain overall system performance acting as focusing devices for further technological innovation (Rosenberg, 1980).[31] These systemic effects can cause a mass of technical and organizational components to move in a particular direction and influence other systems, groups, and individuals to give systems-change momentum (Hughes 1987, p. 76, 54-5).

The distributed trial-and-error experimentation involved in these changes generates cumulative improvements in practical and theoretical understanding. The differential accumulation of technology-specific knowledge, in turn, creates differences in the rates at which different parts of the technological frontier can be developed. As a result, technical change follows cumulative paths or trajectories in which the articulation of demand and the direction of research are guided by expectations of the most fruitful ways forward (Dosi, 1982; Pavitt, 1987, 1999).[32]

The systemic interactions that emerge during this process can lock technologies into path dependent trajectories, particularly if change is subject to increasing returns to scale (where the more it is used the lower the costs become), learning effects (where the more we use something the better we collectively perform), network effects (where information and physical networks become more valuable as they grow in size) and changing expectations as increasing adoption reduces uncertainties about quality, performance and permanence in the market (Unruh, 2000). All these phenomena generate positive feedback loops and strong selection effects that reinforce the use of a particular technology.[33]

As a result, while in early stages of a technology's development there might be considerable flexibility in where it will go, as technical specifications are established and widely adopted, and the size and complexity of the technology increases, flexibility is reduced. Contingent influences can amplify small initial advantages and set technological development on new paths, leading to different long term outcomes. As a result, the final selection of technology is subject to timing, historical circumstance and actors' behaviour rather than optimisation (David, 1985). Inferior options can become difficult to displace even by seemingly superior technologies. The QWERTY keyboard, VHS video and light-water nuclear reactors became dominant designs even though superior alternatives existed (David, 1985; 1975; Cowan, 1990).

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[30] Sociologists discuss this coming together of science and technology to create something very different using the concept of *technoscience,* while this is a useful concept, it can be potentially misleading if it looses the differences between science and technology highlighted above. The existence of cakes doesn't imply that eggs and flour are the same thing.

[31] Hence the definition of systems in terms of components, an archiecture or network connecting them and a control function that guides them towards the systems overall function.

[32] Because technical change is so difficult to predict, these perceptions are structured by shared expectations that guide and co-ordinate activity and resources during the innovation process, and are gradually modified as the technology is developed.

[33] When technologies are first introduced there can be large numbers of hopeful designs, reflecting the uncertainty about how the technology will develop. In the 1890s, for example, there were 3200 different vehicle designs using an internal combustion engine in the USA, produced by 1900 firms. By the 1920s a dominant design had emerged (Abernathy and Utterback, 1978) and increasing returns had reduced the number of firms to a few dozen, and by 1955 the "big three" of Ford, General Motors and Chrysler had 90% of the US domestic and 80% of the global automobile market (Unruh, 2000, 821; Nester, 1997). As a dominant design emerges innovation shifts from products to process improvements, with associated organisational changes and investments in specialised, durable and untradeable assets that reduce the costs of some producers, while driving others out of the market.

This lock-in occurs with ideas as well as artefacts (Starbuck, 2008). Technologies reflect, depend on and reinforce socio-economic relations between people and people, and people and things. Ideas can mutually adapt to one another through a phenomenon called cognitive consonance, where attitudes, beliefs, perception and values become logically consistent when they are simultaneously evoked (Webster and Starbuck, 1988)). This is why in organisations social status, competence, control and organisational attitudes converge (ibid).[34] Technologies, once developed, have a persistence and autonomy that helps structure and reinforce these social relationships in ways that get more persistent as technologies get embedded in their surroundings.

The combination of systemic leverage and cognitive lock-in mean the performance of technologies tends to improve when judged by the standards of the regime, while the standards of the regime get increasingly defined by the technology and can become increasingly inappropriate as the wider world changes. The systemic and, at least partly, autonomous power of technology make it interesting, while they way the direction of technical changes can get out-of-sync with desired outcomes make it concerning.

Discussion and Conclusion

This paper has sought to provide some insight into what technology is, and how it is understood. It has highlighted how technology is a relatively new term, that has changed its meaning and is now applied to something that is distinct from applied science and involves a substantial tacit element. These empirical features then fed into a series of theoretical discussions of how science and technology move between causes and effects in a different directions, have different Speech Act structures, and are created in different ways. This led to a series of definitions of technology that went from it being (1) artificial functions, to (2) being the outcome of an innovation process that changes the world to match an idea, to (3) artefacts, technique and a regime, to (4) being the outcome of a process in which all three coevolve, to (5) to changing in a way that is widely distributed in time and space. Lastly, technology was defined in historical time (6) in relation to the shift from machinery-based towards system-based forms of production, that occurred once the conditions were in place for science and technology to overlap (see Table 1).

Table 1: Different Ways of Thinking about Technology

Way of Thinking about Technology	**Exemplar user**	**Key Issue**
Artefacts that solve problems	Engineers	Takes process as given, solves problems
Outcome problem-solving process	Innovation-Managers	Takes context as given, improves process
Artefacts, technique & regime	Sociologists	Takes history as given, counterfactual context
Co-evolving artefacts, etc	Historians of technology	Explores 'Long view' of history
Distributed co-evolution	Tech-Governance	Systemic interactions
After S&T coincide	Historians of Tech-change	Qualitative difference btw machines & systems
Way of looking at the world	Philosophers	Systems imposed frameworks

Each of these different views reflects different perspectives, different historical timescales, and different interests. As such, they can be tentatively mapped onto different social groups - engineers, historians, sociologists and philosophers, etc. Given the production of modern technology is distributed, this suggests there is potential for conflicting visions.

This is important because bringing science and technology together has enhanced the speed and power of technical change. Previously it involved unguided muddling-

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[34] This causes activities, interaction and sentiments to reinforce each other, so that people resemble their neighbours and organisations develop distinctive norms & beliefs, making social systems resistant to change (Webster and Starbuck, 1988).

through, while now it can be guided by science to significantly reduce the number of redesign cycles that need to be explored to find suitable operational principles. Changes in the technologies that underpin the process of technical change have opened up new technological opportunities. This, unsurprisingly, has made scientific understanding very valuable and changed science in the process.

While the the application of science has increased the internal predictability of technology, it has also enhanced the power of technology which has, other things being equal, decreased our ability to understand and control its external impacts, precisely because they are now so much more extensive. Modern technologies have the power to generate more output (effects) with fewer inputs (causes) by directing energy and changing the structure of systems (including systems of complex abstract thought). This has expanded the intended and unintended impact of technology in time and space, which has delocalised and often fundamentally changed the social distribution of the risks and rewards of technical change (Nightingale et al 2003). One way historians understand modernity is as the period where these risks were managed by nation states (Schott, 2009) with the more recent period as one where they transcend the boundaries and capabilities of individual states (Beck, 1992). Because modern technology can be both destructive and constructive, the complex relationship technology has to our tacit background knowledge is concerning as it has the potential to generate two pathologies in our understanding of what technology is.

12.0.1 Technologies as Gadgets

Firstly, the tacit nature of at least some of our knowledge of technology increases the risk that we fundamentally misunderstand what technologies are. Specifically, we run the danger of attributing the functional properties of the artefact to its intrinsic physics. This way of thinking of technologies as “gadgets” misses the cognitive element, the imposed nature of technological functions, the tacit knowledge needed to develop and operate a technology, and the dependence of technologies on wider connections to complementary devices, institutions and forms of knowledge. It creates a phantom objectivity that reduces the technology to an autonomous artefact, in a seemingly “scientific” way.

While this scientific appearance is enhanced by the technical nature of technical change, it is entirely bogus. It renders artefacts’ dependence on an external environment and its associated social relations between people invisible. The ability of biotechnology to generate drugs, let alone change society, is not a natural, scientific consequence of the intrinsic biophysics of genetic material unfolding through time, any more than the height of an ironing board is a reflection of the physics of its material components. Unfortunately, the technologists and scientists most exposed to a particular technology, maybe the ones most likely to have built up the tacit knowledge that makes its dependence on its external regime difficult to see. Hence it can seem natural for them to frame technological questions in a seemingly ’scientific’ way that reflects their positions and perspectives rather than anything natural. For example, the debate on genetically modified foods is framed in terms of risks and the public’s irrational rejection of a seemingly safe product, when the real reason the products were rejected by consumers was they couldn’t see any benefits.[35]

This pathology is a particular problem with new technologies. Because the future impact and value of early stage technology is uncertain, technologies are initially promissory and only exist in the minds of their promoters. Since they don’t exist yet beyond proof of principle examples, such early stage technologies are typically understood by tacit analogy to similar technologies. By definition these are successful and therefore atypical, given the high failure rate of early stage technologies (Stir-

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[35] Similarly, climate change policy is framed as a scientific question about the likelihood of a particular rise in temperature, when the uncertainties and ambiguities about outcomes are so large as to probably make this an impossible question to answer, while the real issue about what to do about it, is overlooked.

ling, 2013). Technologies' dependence on tacit knowledge can create a false sense of certainty about outcomes and their likelihood, which overemphasise potential benefits and diverts attention away from how they emerge, what alternative options are available, and the opportunity costs involved (Stirling, 2013). Needless to say the inherent uncertainty and need for shared expectations to guide future activity offers plenty of opportunities for over-confident snake-oil salesmen and charlatans to hype the revolutionary potential of gadgets (see Wynne, 1992 for a useful discussion of technical uncertainty).

12.0.2 Technology as a way of seeing the world

Secondly, the tacit nature of technological knowledge can lead to a pathology where we mistakenly take a particular way of looking at the world as natural. When developing technology we look at our subject in instrumental terms as something to change, reorganise and modify to generate benefits. If this becomes second nature, we can mistakenly think it is natural. So while seeing technology as gadgets mistakenly assigns the properties of technology to artefacts, here they are mistakenly assigned to the world. Again this misses all the messy tinkering that is needed to get technologies to function, and again it can be subject to a bogus sense of being "scientific". While its self image is one of bravely seeing through the messy complexity of the world to an underlying scientific reality just waiting to be improved, it instead imposes a framework of controllable mechanisms on top of a reality that doesn't necessarily match it.[36]

Such a view of the world is often proposed to reflect scientific rationality or an engineering viewpoint, but is deeply unscientific and the anti-thesis of good engineering design, which elicits users' normative framings of requirements and comes up with creative solutions that address them.

This way of looking at the world, by contrast, generates a distored view of ourselves, our motives and the world. To see the world as a thing 'out there' to be manipulated, we have to think about ourselves as free and rational to the extent our identity is no longer defined by *anything* external (Taylor, 1995). Secondly, this way of seeing the world can be applied to the normative ends that motiviated its application in the first place, allowing them to be seen in instrumental terms.[37] Thirdly, seeing the unpredictable world as a predictable technological mechanism projects onto it a clean, reductionist, controllable causality in which complex entities are determined and explanable by their component parts. This is scientifically naive (Dupre, 1993). Hence, society is explained by individuals, all the way down to molecules, atoms and finally subatomic particles (Dupre, 2001).[38] Scott's *Seeing like a State* captures the consequences of these distortions: imposing a framework of prediction on unpredictable nature means that plans do not match reality, normative constraints on behaviour are then over-riden for instrumental reasons by people who see themselves

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[36] As more of our experiences are structured by technology and made to behave in ways that are predictable enough to be controlled, predictabily becomes second nature and we can mistakely think it is natural, thereby overlooking all the invisible infrastructure needed to make technological systems work reliably (Nightingale, 2004). This view is amplified by the mistaken belief that deterministic laws of nature that apply in simplified scientific models apply directly to the real world, outside the artificial conditions of experimental apparatus that has been deliberately created to replicate the unnatural conditions in the model world.

[37] Conservative philosphers, from Burke onwards, have now been joined by Green philosphers in highlighting that this creates a inbuilt tendency for this pathological style of thinking to run away with itself and 'devour its own children'. The tendency to see the price of everything and the value of nothing, can end up with normative frameworks that can justify anything as a seeminly logical consequence of initialy desired end.

[38] As we have seen, symmetry breaking means that this reductionist vision is misleading. The history of 20th century science has been to show how this supposedly 'scientific' worldview is false (Dupre, 1993; 2001). Unfortunately, the bogus scientific credentials of this way of looking at society help justify a range of theories, that are often poor at describing the world, but useful for formulating operational principles for policy, even if the resulting policies have implementation problems because of the mismatches between the world and the frameworks highlighted earlier.

as morally empowered to force the population to adapt to their mistaken plans.[39]

Importantly, this way of looking at the world ends up hiding technology.[40] The hierarchical, mechanistic view of nature has little room for mind-dependent technology. Traditional post-Quinean philosophy, for example, adopted its mechanical framework and typically defines something as real if it can be analysed by the natural sciences and reduced to the particles studied by physicists. Since technologies are human-dependent objects, they do not live up to this (rather demanding) criteria for being real, which has made technology largely invisible in philosophy and the social sciences (Meijers, 2009). So, while there are 46,240 entries for science in the *Philosopher's Index* (1940-2009), there are only 1,250 for technology (*ibid*). Moreover, despite the significant overlaps between science and technology, there is not a single entry for technology, artefact, engineering or design in the 2000 pages of two recent handbooks of the philosophy of science (Meijers, 2009, 1).[41]

This suggests a final way of thinking about technology linked to these two pathologies:

> Definition 7: Technology is a way of seeing the world in instrumental ends-means terms, that projects a bogus scientific objectivity, hides the power of technology, and mistakenly presents things as natural when they are not.

This view of technology, found among a subset of Continental philosophers and social critics, often leads to a very negative critique of 'technology', as ironically it adopts the same top down, reductionist perspective as the thing it is attempting to critique.[42] This does capture something important, that is reflected in our increased scepticism towards technology compared to the public of the 1950s. However, it misses how technologies can address real problems because it sees benefits (i.e. of drugs relieving suffering) as 'really' the expression of Power (with a capital p). This isn't a critique of technology as they understand it, but an expression of its power. If the tacit nature of technology helps create and maintain a reductionist, mechanistic perspective that makes the world seem fit for technical change, but hides the power of technology in the process (even among people whose job it is to see it), we have come full circle. It implies the 'of' in the 'sociology of technology' or the 'economics of technology' or the 'philosphy of technology' can reflect the subject matter of the respective body of analysis, or it can reflect the subject is in an ownership relationship and operate like the 'of' in 'the slave of the master'.

12.0.3 Final Thoughts

These two pathological ways of looking at technology have practial and normative implications. On a practical level, they both lead to a significant under-estimation of the difficulty of getting technology to work. By missing the 'invisible infrastructure' of technical change they imply that technologies that work in one setting, will work in another - because that ability is either instrinic to the artefact or a feature of the

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[39] Heidegger, amongst others, saw modern technological society in terms of the cummulative rise of a stance of dominance towards nature. Jan Patocka and Leszek Kolakowski are more subtle.

[40] Technology that behaves in deterministic ways can make determinisim seem natural - almost second nature. Hacking (2001) highlights Cassier's point that determinism wasn't an idea until 1872 when society had been made more determnistic by technology.

[41] It might be worth pointing out that this technological way of looking at the world frames technology as applied science.

[42] This can happen if this view of the world turns its attention to normative arguments or claims to truth. This generates a relativistic turn in which truth is reduced to power, which can nulify the intentions that motivated its application in the first place. As Wollhin highlights "The vocabulary of postmodernism, with its antipathies towards essentialism, centred discourse, foundationalism, and historical narrative, has served to disable its theorists from confronting the basic character of contemporary power-formations whose precise characteristics are to be: centralized yet quick to react, essentially economic, founded on corporate capital, global, and best understood in terms of developments over time. The cascades of 'critical theory' and their postures of revolt, and the appetite for theoretical novelty, function as support rather than opposition." (2010; 567).

world. In reality technology transfer isn't easy. If technologies could be simply moved around the world, or from firm to firm, then productivity convergence would be a simple process. Instead, we find its very hard, and in some instances we find that introducing new technology can be actively disruptive.

They also overlook normative issues related to technology. The increasing impact of technology means there are legitimate public policy concerns about technology, particularly 'revolutionary' technologies promoted by snakeoil salesmen. For example, the public has an interest in emerging technologies funded by the public; technologies that have the potential to create significant benefits or harms through intended use or unintended mis-use at scales that do not allow individuals to opt out; in technologies that affect the conditions of common life and close down individuals' future options in ways that constrain their freedom and future flourishing; and in technologies that relate to living things and carry particular religious or ethical interest (Nuffield, 2013; Stirling, 2013).

Misunderstanding technology as "gadgets", whose socially beneficial functions naturally unfold, ignores how new technologies can change the social distribution of risks and rewards and generate profound and irreversible changes in commercial, social and physical environments. These changes different people in different ways, creating ambiguity about their value and making technology assessment an inherently political process (Stirling, 2013). The pervasive influence of these pathologies creates an overemphasis on technical solutions to social problems and leads to naïve inflated expectations about technology, often buttressed by on distorted popular visions and unrealistic claims to scientific certainty, that overlook the inherent unpredictability of technical change (ibid).[43]

At the same time, the large scientific infrastructure that has developed to investigate the social, statistical and temporal distribution of the risks generated by technological systems, is not counter-balanced by independent analysis of the likely distribution of benefits. This makes informed public debate, and effective strategic decision making more difficult than it need be. Percieved problems with the precautionary principle might therefore reflect problems with the institutional settings in which it operates rather than with the wisdom of taking uncertainty seriously.

Hopefully this paper has laid out a series of useful ways of thinking about technology that can guard against this. It hasn't come up with a single definition or correct way of thinking about technology, because technology isn't the sort of thing that has a single definition. In fact, thinking a single definition exists reflects an implicit aceptance of a way of understanding the world defined by technology in the sense explored here i.e., where we are apart from the world and our knowledge of that world consists of representations of things that exist as clean cut categories in a reductionist, mechanical universe (Lakoff, 1987; Taylor, 1995). The fact we can't define technology so neatly (Lakoff, 1987), and the fact functions are imposed, so that our intentional understanding is part of technology, highlights how misleading this view is. Understanding that there are different views will hopefully allow us to see the problems with this way of thinking and so understand technology a little better. This is important because by seeing in ourselves how technology can influence how people see technology, we can see for ourselves how it can distort our own thinking and actions. Hopefully, we will then act in a more informed way, as judged by others, in influencing how technology is designed, built and used.

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[43] Seeing technology as applied science similarly overlooks the dependence of technology on projected normative frameworks and the extent to which technical change has a direction as well as a rate (Stirling, 2013). People who disagree about the direction of technical chance can then be framed as irrational, anti-science Luddites (ibid; Nightingale, 2013c).

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