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Foresight in an unpredictable world

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Foresight in an unpredictable world

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Unpredictability has two main sources: epistemic uncertainty and ontological unpredictability. When disruptive and downstream innovations become frequent, ontological unpredictability becomes increasingly important for innovation policy and strategy. The analysis of the nature of ontological unpredictability explains why future-oriented technology analysis and foresight frequently fail to grasp socially and economically important technical developments and clarifies why policy, strategy, and future-oriented analysis need to move beyond evidence-based approaches.

Keywords: unpredictability; ontological expansion; anticipatory systems; innovation; creative evolution

Introduction

Predictions about future almost always fail. In this paper, the epistemic and ontological causes for this failure are described and their implications for foresight, innovation policy, and strategy are explored. The paper introduces the idea of 'ontological unpredictability' and shows how innovation leads to unpredictability that cannot be removed by more accurate data or incremental improvements in existing predictive models. Based on the presented analysis, it highlights some methodological implications for future-oriented analysis and policy-making.

The paper aims at a conceptual contribution that builds on several disciplines, ranging from innovation and technology studies to a Bergsonian analysis of creative evolution, theory of autopoietic and anticipatory systems, and cultural–historical theories of cognitive development and social learning.

The paper is organised as follows. The next section introduces the two sources of unpredictability: epistemic uncertainty and ontological unpredictability. The following section then further elaborates the idea of ontological unpredictability in the context of innovation theory, showing that downstream innovation leads to a practically important form of ontological unpredictability. It then introduces Bergson's model of creative evolution, showing that it leads to ontological expansion, and illustrates this using the expansion of mobile phone industry as an example.

The paper then makes the claim that technological change can be understood as an especially human form of Bergsonian élan vital or creative flux. In contrast to Darwinian models of evolution where selection weeds out unsustainable developments, in the Bergsonian model, living processes

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are active generators of novelty and evolution is an essentially open-ended and non-optimising process. We use a simple illustration of a mountaineer to illustrate such an open-ended process of path-finding and use some ideas from cultural–historical theory to argue that modelling the directionality of the innovative élan requires analysis of progress at several time scales.

The paper then moves to a more detailed analysis of the phenomenon of ontological unpredictability. For this, we describe and expand Robert Rosen's analysis of the nature of modelling and the relationships between natural and formal systems.

Based on these conceptual developments, the paper then proposes some practical implications for future-oriented research and policy. The analysis described in this paper essentially indicates that innovation and predictive models are theoretically incompatible. Policy-relevant future-oriented analysis, therefore, needs to emphasise processes that support insight, intuition, and innovation, instead of relying on data collected using historically important categories and measurement instruments. Economic and social trends measure what used to be important and often miss things that will be important. To understand how innovation generates progress, we have to reconsider some key concepts that underlie future-oriented analysis and strategic management.

Two sources of unpredictability

In much of contemporary thinking, failures in prediction indicate a need to engage in further study and research. If we only had accurate data and models, we could have good predictions. In this view, our data and models are only approximations, and epistemic progress can occur through incremental improvement. Although there may be cognitive and economic limitations, in this view, the levels of certainty and rationality could be increased by better evidence and knowledge, and progress can be measured against an ideal of perfect knowledge.

At least since the 1970s, it has been well understood that even when the world unfolds in a completely deterministic fashion under well-known natural laws, its complexity makes it impossible to perfectly know its future. Already relatively simple systems have interactions, nonlinear dynamics, and sensitivity that lead to chaos, strange attractors, and catastrophes that make a good prediction hard to find (Lorenz 1963; Ruelle and Takens 1971; Thom 1972; Nicolis and Prigogine 1977; Feigenbaum 1978; Haken 1981). For all that we know, physical nature can be indeterminate.

Social scientists (Goffman 1959; Giddens 1984; Luhmann 1990; Beck, Giddens, and Lash 1994) have further emphasised the point that reflexivity in thought and action creates a delicate balance between predictability and unpredictability in social systems and interactions. As soon as we have an explicit theory of human or social behaviour, it influences the way we think and live, thus, in general, making the theory obsolete and prediction futile.

In economics, Knight (1921) differentiated between two kinds of uncertainties. One he labelled as risk and the other as 'true' uncertainty. Risk, according to Knight, was associated with events where outcomes could be known using probability distributions, either *a priori* or from statistics of past experiences. When the distribution is known, the associated uncertainty is measurable and can always be managed as a fixed cost of doing business. True uncertainty, in contrast, emerges when the situation cannot be classified as an example of a generic group of similar situations. According to Knight, in the latter case, the concept of probability or chance is simply inapplicable. Knight maintained that most business decisions are made in unique contexts that make statistical inference impossible and which require intuition and speculative guesses. Entrepreneurs live under true uncertainty, irredeemable ignorance, and failing foresight, which in competitive markets remains the only source of profits.[1]

Epistemic uncertainty

Integrating the numerous extant typologies of uncertainties proposed in the literature, Walker et al. (2003) distinguished two sources of uncertainty. *Epistemic uncertainty*, according to these authors, is uncertainty due to the imperfection of our knowledge, which can be reduced by more research. *Variability uncertainty*, in turn, is due to inherent variability of empirical quantities, generated by the inherent randomness and unpredictability of natural, behavioural, and social processes. Following van Asselt and Rotmans (2002), they characterised variability uncertainty as 'ontological uncertainty'.[2]

The ontological uncertainty of van Asselt and Rotmans and Walker et al. is about uncertainty of attributes associated with given objects. Although the attributes of the objects can be uncertain, random, and perhaps unknowable, the ontology itself is taken for granted and presumed to be known. This concept of 'ontological uncertainty' thus somewhat paradoxically requires that there is no uncertainty about the underlying ontology. Therefore, we use the term epistemic uncertainty below to cover both variability uncertainty and epistemic uncertainty.

In this paper, the focus is on a specific form of unpredictability that looks terminologically similar to ontological uncertainty, but which is fundamentally different from it. As uncertainty tends to be an inherently epistemic concept, we distinguish between (epistemic) *uncertainty* and (ontological) *unpredictability*.

A central claim made in this paper is that ontological unpredictability is becoming the dominant form of unpredictability as communication and information networks make distributed downstream innovation increasingly visible. Ontological unpredictability thus becomes important for technology analysis, foresight, and strategy, as well as for characterising the limitations of evidence-based policy-making in innovation-intensive societies and economies. In the next section, we further clarify this concept.

Ontological unpredictability

The nature of ontological unpredictability can most conveniently be understood in the context of innovation theory. The prototypical narrative of the traditional Western model of innovation can be found from the first chapter of Genesis. The 1769 version of King James Bible tells us how cattle and beasts are created:

> And God said, Let the earth bring forth the living creature after his kind, cattle, and creeping thing, and beast of the earth after his kind: and it was so.
>
> And God made the beast of the earth after his kind, and cattle after their kind, and every thing that creepeth upon the earth after his kind: and God saw that [it was] good.

This model of creativity underlies much of innovation research still at present. It assumes that as new entities are brought to life, their nature is well defined. Cattle, in this model, can clearly be separated from beasts. All the creation can be categorised at the moment of creation.

In practice, such a model assumes a creator who has a blueprint of the different types of animals and entities that will populate the world. It also assumes a creator who does not learn, experiment, tinker, revise her plans, or innovate. After the act of creation, the beasts remain beasts and cattle remains cattle.

From a sociological, anthropological, and ethnographic point of view, this model is clearly a problematic one. Animals, as well as technologies, are domesticated in a historical process. For ordinary human beings, what used to be a beast can one day become cattle. The nature of the beast depends on our relation with it. If we run as fast as we can and climb into a tree, the animal is a beast. If we milk the beast, it becomes cattle. However much we study the attributes and features of the animal, we will not be able to tell whether it is a beast or not. This knowledge cannot be found from the animal itself. The appropriate way to categorise the object of study depends on the role it plays in the current social practices.

Downstream innovation and relational monsters

The Genesis essentially depicts a linear model of creation where an 'upstream' heroic innovator is the true source of novelty. In this model, the narrative structure simultaneously generates the key categories of 'creator', 'object of creation', and 'user' and a directed linear model of impact and causality that makes these categories salient. It organises chaos into cosmos and, as a side effect, creates a specific model of reality and ontology.

Although the linear causality of this model is now often rejected and the role of users is emphasised, the underlying static and pre-existing ontology is still frequently taken for granted. Also the common distinction between radical and incremental innovations implicitly relies on prescient classification of the innovation in question. For example, the idea that radical innovations emerge as 'hopeful monstrosities' that only gradually realise their true promise (Tushman and Anderson 1986; Mokyr 1990, chap. 11; Bower and Christensen 1995) assumes that we know the dimensions on which we will measure their 'beastliness' at the point of their emergence. In practice, such 'ugly ducklings' of evolution can be defined as ugly ducklings only retrospectively, when we already know that they are not (Tuomi 2002; Taleb 2007).

In contrast to this biblical ontological model, below we adopt a model of constant creation that relies on a different ontology. In this model, innovation occurs when social practice changes.

The history of innovations and technical change shows that 'heroic innovators' are often located in the downstream. Innovative ideas abound, parallel innovation is frequent, unintended uses become drivers of development, and socially and economically important innovations are often invented several times before they eventually start to have real impact. The true innovative step, in general, occurs when a potential user group finds a meaningful way to integrate latent innovative opportunities in the current social practice (Tuomi 2002).

In contrast to the traditional heroic 'upstream' innovation model, downstream models emphasise the active role of current and future users. In the early work of Von Hippel (1976, 1988), the users were innovative users of existing products. In models that emphasise the role of social practices and social interaction as the key loci of innovation (Engel 1997; Brown and Duguid 2000; Tuomi 2002; Oudshoorn and Pinch 2003), downstream innovators also include creative members of communities of practice. For example, in the multifocal model of Tuomi (2002), new technical functionalities and propensities are in effect thrown from the 'upstream' to a 'downstream' field of interacting social practices, and new user groups and new uses mutually construct each other. Innovation and social learning in the context of the local downstream systems of meaning then become key drivers for the evolution of technology.

This view allows for the fact that some innovations are more radical and revolutionary than others. Some innovations are simple improvements of existing practice. Others, however, can appropriately be called revolutions, and their realisation requires power struggles (Hughes 1983; Callon, Law, and Rip 1986; Bijker, Hughes, and Pinch 1987; Latour 1996) as well as new world views, social arrangements, and systems of categorisation (Schon 1963; Fleck 1979; Dosi 1982; Perez 1985; Garud and Rappa 1994; Bowker and Star 1999; Geels 2005). It is, however, impossible to categorise a particular innovation based on the characteristics of a technical artefact before it is used. The proper unit of analysis of innovation is thus 'innovation-in-use'. The same artefact can be used for many different purposes in many different social practices, each with its own developmental trajectories. This leads to a relational epistemology that is structurally different from the traditional objectivistic and empiristic models of epistemology. It also shifts the locus of innovation from the 'upstream' to the 'downstream'.

A practical consequence of this relocation of locus of innovation to the downstream is that human upstream inventors rarely know, or can know, what their inventions will be. The dominant constraints and resources for innovation are often far beyond the reach and control of heroic upstream creators. Innovations become real in the context of use, and this requires stocks of knowledge and systems of meaning that are located in communities of users and social practice. The true nature of the beast is revealed only when someone domesticates it.

Ontological expansion and creative evolution

Downstream innovation in the history of telephony

If asked about the history of the telephone, many technology students could easily name Alexander Graham Bell as its inventor. Yet, in his patent application from 1876, Bell tells us what the telephone is about:

> By these instruments two or more telegraphic signals or messages may be sent simultaneously over the same circuit without interfering with one another.
>
> I desire here to remark that there are many other uses to which these instruments may be put, such as the simultaneous transmission of musical notes, differing in loudness as well as in pitch, and the telegraphic transmission of noises or sounds of any kind. (Bell 1876)

As Fischer (1992) has documented in detail, for many decades after the telephone was invented, it was marketed mainly for business use. It was often understood either as a new form of telegraphy or as a broadcast medium. Telephone entrepreneurs tried to use the telephone to broadcast news, concerts, church services, weather reports, and stores' sales announcements. The telephone was also expected to be used for voting campaigns and long-distance Christian-Science healing and to broadcast lullabies to put babies to sleep (Fischer 1992, 66).

Social conversations and 'visiting' over the telephone were not uses that telephone was supposed to serve, and almost the first five decades of its history, industry actively discouraged such use. This social use of the telephone was basically invented by housewives in the USA, in particular, by those in the Midwest, around the first decade of the twentieth century.

The challenge of ontological unpredictability can thus be formulated in a simple way: How can we predict the number of cattle or the impact of a new technology, when we only retrospectively know what we are talking about? If the beast changes its nature in the course of evolution and becomes essentially a new thing, how can any model capture its key ontological dimensions?

Henri Bergson explored this question in great depth over a century ago. In Creative Evolution, he argued that both mechanistic and teleological approaches fail to explain novelty. In mechanistic approaches, future unfolds in a deterministic way and there is no space for truly novel forms. In finalistic and teleological approaches, on the other hand, the future is pre-ordained as a perfect blueprint. Both mechanistic and finalistic explanations of evolution and emergence, therefore, have to be wrong. According to Bergson (1983), 'they say the same thing in their respective languages, because they respond to the same need' (45).

In Bergson's analysis, evolution is a process that creates continuously new forms. A key starting point for Bergson was the belief that evolution is truly creative, and novelty is not only recombination of already existing forms or unfolding of a pre-determined future. In contrast to the Darwinian model of evolution, where living beings are essentially stochastic samples and passive subjects for environmentally driven selection, Bergson argued that development is actively pushed by all living beings. With some simplification, this 'élan vital' could perhaps be called 'the process of life'. It is 'teleology in action', but generated from the inside of the living being. In simple living beings, it is instinctive, according to Bergson. For humans, this directional push is also conscious.

In Bergson's theory of perception and cognition, the world presents itself to living beings in two essentially different forms. Intuition and instinct allow us to grasp the ongoing process and flow of life. Out of this continuity, intellect, in turn, constructs a world that consists of discontinuities and potential breaking points. Although the process of life transpires in a continuous world where distinctions are non-existent, our intellect is a tool for intervention. It thus tells us how to break the continuity and create distinctions that matter. The distinctions that our intellect generates are not arbitrary, however; instead, they reflect our capacities to act. According to Bergson, we see what makes a difference, and this, in turn, depends on our space of possible action and intervention.

In the Bergsonian model of evolution, the process of life creates new forms and new possibilities for action. In contrast to the mechanical time of physical sciences, the Bergsonian 'durée' of living processes therefore has direction and irreversibility. The continuous process of creative evolution thus creates as its mirror image an ontological reality that expands.

Ontological expansion in the mobile space

This process of ontological expansion can be illustrated by comparing the evolution of the biological eye and the mobile telephone.

How can the nature invent a complex system such as the human eye? The emergence of an eye cannot result from following some mechanistic principles that add up to a functioning eye. Nor can the elements of an eye be generated in a teleological process that aims at producing an eye. The idea of an eye presupposes vision. Yet, the evolution has produced a large variety of similar structures for eyes again and again, directing development towards practically useful directions (Mead 1907).

The Bergsonian explanation is that living beings create a 'proto-eye', which is originally used for a different purpose. After it evolves to a point where it becomes useful for vision, a new domain of action emerges. This domain is linked with the capability to make distinctions based on vision. At the same point, a 'world of vision' is created, simultaneously with the functional organ that we now can call 'the eye'. At this point, we can also start to tell a story about the 'proto-eye' and retrospectively find its precursors.

In mobile technology, global system for mobile communication (GSM) short messaging is created in a similar fashion. First technology designers implement short message service (SMS) functionality with the aim of sending control, broadcast, and pager messages to phone users. After the functionality becomes available, teenagers start to use SMS for communicating with each other. At that point, social practices start to change. Messaging becomes a key driver for development and profit in the telecom industry, and telecom operators start to write 'messaging' in their strategic plans and marketing material. Ontological reality expands. After the new domain of reality moves from periphery to the centre, and messaging becomes an established social practice, stories of heroic innovators emerge telling how SMS functionality was devised by clever engineers in the GSM standardisation groups in the mid-1980s.[3]

Ontological expansion thus generates a new 'phenomenological domain' that cannot be reduced to earlier ontological realms. After the wide adoption of SMS messaging, the phone is not any more what it used to be. We may still use the same word and the device still may have the same physical characteristics as before. The meaning of the device, however, has changed. Information gathered on previously important characteristics simply misses the essence of the thing.

Innovation as creative evolution

According to Schumpeter, innovation can be defined as a historic and irreversible change in the way of doing things. Although Schumpeter went on to further define innovation as those changes in the production function that cannot be decomposed into infinitesimal steps, he did this to add a historical and irreversible element in the prevailing equilibrium models in economic theory. As Schumpeter (2005, 138) put it: 'Add as many mail-coaches as you please, you will never get a railroad by so doing'.

Many innovation theorists since Schumpeter have focused on the economic aspect of innovation. More broadly, innovation is, however, about revolution, and it is a fundamentally social phenomenon. Important historical innovations such as fire-making and the creation of the Phoenician alphabet or the wheel are primarily social innovations. Some revolutions remain small and can be characterised as incremental, parametric, or adaptive innovations. Sometimes revolutions are more radical. The essence of innovation, however, is in its ontological discontinuity and in its capacity to create directionality in time.

Technical change as élan vital

Innovation thus creates phenomenologically new domains of being and action. But what directs and drives this process? One possibility is to take the Bergsonian model of evolution seriously and define technical change as a specifically human form of élan vital.

For Bergson, élan vital was the basic characteristic of all life, the moving ahead towards undefined directions that can perhaps only be described as the process of life. The process is not determined by a plan or programme, and it does not optimise any given function; instead, it is driven by an endogenously created force. In practice, we create imaginations (Rubin 1998; Miller 2007) and expectations (Borup et al. 2006) that provide us temporary stepping stones on the way ahead.

We may illustrate the expansionary character of this process using alpinism as a metaphor. When a mountaineer climbs a mountain face, at each hold, she looks for a next possible place to cling, grip, jam, or stand. She traverses forward one step and one grip at a time. During the ascent, she places camming devices, nuts, pitons, and anchors at places where they can protect the climb. The route is revealed by climbing it. At each step, progress is limited by the reach of the climber. After reaching a point that satisfies as a mountain top, the climber can look back and say 'Aha, this is the route to the top'. The directionality of innovative élan may therefore have both local and global directionality (Raven and Geels 2010, 89), and it needs to be described as a complex process that transpires in several different time scales in parallel (Tuomi 1999, 203).

One possibility is to use Leont'ev's (1978) hierarchical model of human activity, which decomposes socially motivated and specialised *activity* into goal-oriented *acts* and further into concrete observable *operations* that implement the acts.[4] In this hierarchical structure, the higher levels provide the context for lower level meaning. At the level of goal-oriented acts, progress may be defined as successful problem-solving, evaluated in the context of a specific social activity. At the level of operations, progress, in turn, can be defined as the adoption of new tools and technologies that effectively implement the operations that are needed to perform goal-oriented acts.

A specific activity thus generates a socially shared ontology that allows problem-solving and problem definition to occur within this ontology. Activities, thus, can be associated with an underlying thought community (Fleck 1979), community of practice (Brown and Duguid 1991; Lave and Wenger 1991), and community of practitioners (Schön 1983; Constant 1987) and with specialised systems of knowledge and meaning (Polanyi 1998; Knorr Cetina 1999).

In practice, the upward movement of most mountaineers does not occur in an inert external environment. The environment is rarely a static result of sedimentation, and sometimes mountains feel like anthills under construction. As many authors (Haldane 1931; Whitehead 1978; Maturana and Varela 1980; Lewontin 1983; Varela, Thompson, and Rosch 1991; Nishida 2012) have emphasised, the environment–subject distinction fails to account for the mutual co-determination and co-evolution of living beings and their environments. Yet, the movement towards future occurs in a context that can often be taken to be static in relation to the time scale of present action. In creative evolution, at each horizon of action, we rely on a temporary blueprint of the world. This is another reason for why we need to split the élan into multiple parallel processes that occur in different time scales.

The alpinist model is, in fact, a reversed version of the natural drift model of evolution proposed by Maturana and Varela. In their original depiction of natural drift, Maturana and Varela (1988, chap. 5) described the process of evolution using a metaphor of water drops rolling down from the top of a mountain. In this model, Darwinistic selection may weed out those developmental forms that are incompatible with survival and reproduction. Darwinistic models, however, are inadequate for explaining the process of evolution, as evolutionary change is strongly underdetermined by selection (Varela, Thompson, and Rosch 1991, 195). In this regard, there is no difference between, for example, business organisations and biological organisms. Profitability may be a boundary condition for survival for business firms in modern capitalism, but it obviously does not determine what happens inside this boundary. Real organisations live in environments where the environment and the focal firm co-evolve and mutually define each other and where many different business models and ecosystem may succeed.

Although the Bergsonian élan can be rather opportunistic, at social and cognitive levels, it is also driven by an internally generated push, for example, the speculative profit opportunities of Knight or the idiosyncratic individual interests of Hayek and the more collective tacit understandings of progress highlighted by Polanyi (Mirowski 1998; Jacobs 2000). In practice, simple tinkering may also be important. Schön (1987, 31) illustrated such a process by recounting Edmund Carpenter's description of the Eskimo sculptor patiently carving a reindeer bone, examining the gradually emerging shape and finally exclaiming 'Ah, seal!'.

Anticipation under ontological uncertainty

Ontological expansion makes anticipation a challenging task. To understand this task, it is useful to recall Robert Rosen's work on anticipatory systems.

According to Rosen (1985), anticipatory systems are systems that contain predictive models, allowing future to have an impact on the present:

> To take a transparent example: if I am walking in the woods, and I see a bear appear on the path ahead of me, I will immediately tend to vacate the premises. Why? I would argue: because I can foresee a variety of unpleasant consequences arising from failing to do so. The stimulus of my action is not *just*

> the sight of the bear, but rather the output of the model through which I predict the consequences of direct interaction with the bear. Or, to put it another way, my present behavior is not simply *reactive*, but rather it is *anticipatory*. (7)

An anticipatory system, therefore, needs to include a model that generates predictions. In some cases, the model can be 'hardwired' in the biological system. For humans, anticipation is less hardwired, and we can continuously adjust our expectations and predictive models.

Humans are also able to use scientific models for prediction. Scientific models create linkages between natural and formal systems. In Rosen's terminology, natural systems include stones, stars, solar systems, organisms, automobiles, factories, cities, and any other entities in the world where a set of observable qualities can be related. Natural systems are the substance matter of sciences and what technologies seek to fabricate and control. Natural systems are at least partially constructions of the human mind, but natural selection and the linkage between action and cognition weed out models that are incompatible with the world.

Natural systems change their states based on interactions between the system elements. These interactions in natural systems are what we usually call causality. Simple observation of a natural system, however, can never tell us anything about the relationships between the observables. Relationships between qualities are never observable as such. We can observe correlations, but there is no natural way to extrapolate from correlations to causal relations. To make this jump, we need to relate the natural system with another, formal, system, where predictions become possible.

The crucial point for Rosen is that time works differently in natural and formal systems. In natural systems, time separates events into two classes: those that are simultaneous with each other and those that are ordered as predecessor and successors. The predecessor–success relation generates causality. In a formal system, in contrast, causality is expressed in structural or logical relations that remain true independent of time, and time becomes a parameter that can be used to label system states. In practice, this means that if the formal model is good enough a representation of the natural system, we can use the formal system to find out the state of the natural system in some future point of time. This will allow us to test the implications of alternative imputed relationships between the observables. We can observe a natural system, create hypotheses about the unobservable causal relationships, fast forward the formal model to a future point of time, and check whether our natural system actually ends up in that state or not. This, indeed, is the only way we move from simple correlations to theoretical models.

The modelling relation, as depicted by Rosen (1985, 74), is shown in Figure 1. To create a formal model, we have to encode the states of the natural system into corresponding states of the formal system. Then we can infer or predict the impact of causality in the natural system by using the rules of inference in the formal system.

In a somewhat reflexive way, the way we construct a natural system depends partly on our capacity to successfully model it. In practice, we have to experiment with alternative systems of encoding to find one that pragmatically fits the task at hand. Indeed, speaking informally, 'a state embodies that information about a natural system which must be encoded in order for some kind of prediction about the system to be made' (Rosen 1985, 75). If the nature is a lock, we try different keys until one opens the lock. In general, we perceive nature as perceivable qualities, categorise its phenomena based on recurrences and regularities, and impute causality on it based on predictive models.

Causality, in particular, cannot therefore be 'found' from the nature. It is a reflection of a predictive model created through our cognitive effort. Science makes use of logical and

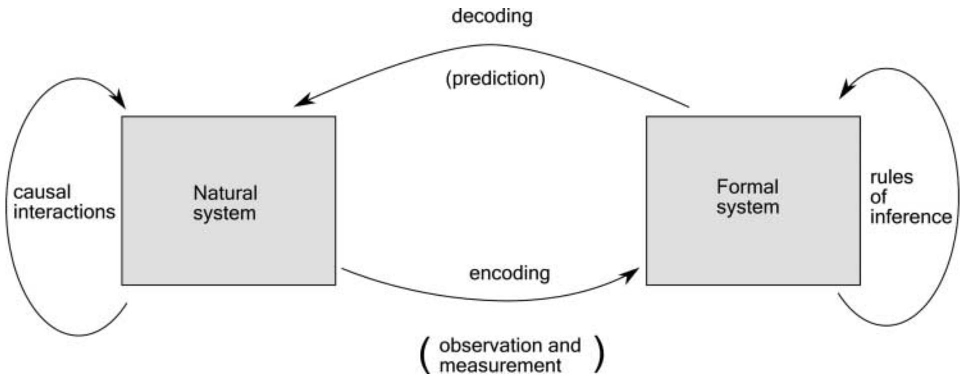

Figure 1. Modelling relation according to Rosen.

mathematical models that make predictive statements particularly efficient and allow, for example, the construction of those artificial natural systems that we usually call technology.

Rosen clarified the modelling relation in considerable theoretical and conceptual RIGOUR. His description, however, leaves somewhat open the question how we come up with the natural systems in the first place. Rosen combines here a partly Bergsonian explanation, emphasising the links between possibilities for action and perception, a constructivist view on the importance of active human cognition-creating models of the world, a Darwinian terminology of natural selection, and a somewhat positivistic view that the environment provides the invariants and qualities that provide the basic building blocks of perception.

Without exploring these in any detail,[5] we can simply fill in the missing piece of Rosen's depiction of the modelling relation. This is incorporated in Figure 2.

In Figure 2, we purposefully locate natural systems and formal systems together. This is because natural systems are also cognitive constructions, partially based on existing anticipatory models and partially on the available repertoire of cognitive categories. The actual interactions of the world transpire on the left-hand side of the figure, behind a 'phenomenological veil'. On the right-hand side, time is a parameter that can be used to label system states and demarcate between causes and effects. On the left-hand side, time is the creator of irreversibility and novelty. In other words, the left-hand side is the generator of innovations, as defined by Schumpeter.

The fundamental reason for ontological unpredictability is, therefore, the fact that predictability only emerges as a cognitive phenomenon. Predictability requires anticipatory models that, in turn, require a fixed ontology.

We construct natural systems and their associated predictive models by abstracting the lived reality. As Bergson (1988) pointed out, abstraction itself relies on memory. This means that both natural systems and their predictive models are necessarily to a large extent retrospective. We see the world in a way that used to be interesting and relevant for us. In slightly more provocative terms, predictive and formal models live in a phenomenological world that is fundamentally a reflection of the past.

Using Figure 2, we may now reformulate the distinction between epistemic uncertainty and ontological unpredictability. Epistemic uncertainty is located on the right-hand side of the figure. It arises because a natural system can be constructed using inappropriate categorisation systems, because the natural system may be mapped into inaccurate predictive models using codings that leak information, and because the observables can be measured with error. Ontological

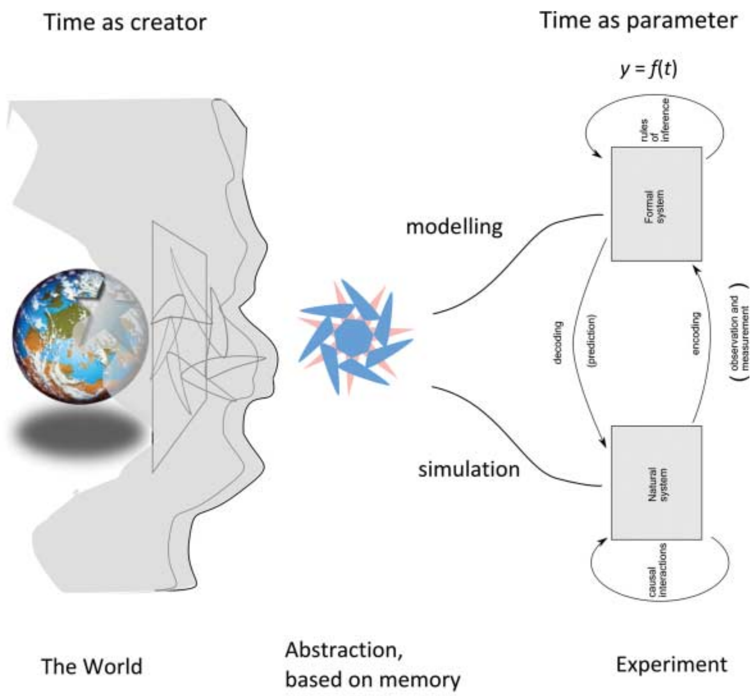

Figure 2. Modelling in the context of the phenomenological veil.

unpredictability, in turn, arises because creative evolution operates on the left-hand side of the figure, introducing novelty that irreversibly changes natural systems and makes their predictive models obsolete.

Implications for foresight and future-oriented analysis

What are the practical implications of the above conceptual analysis for foresight and future-oriented analysis? There are some methodological as well as pragmatic implications.

Ontological expansion and foresight research

The above discussed concepts of unpredictability and ontological expansion shed some new light on recent discussions on foresight research. Here we touch only two issues: weak signals and scenario methodologies.

In future-oriented research, the nature and implications of ‘weak signals’ have been actively debated during the last few years (Mendonça et al. 2004; Rossel 2011; Holopainen and Toivonen 2012). We can use the above analysis to gain some novel insights into this debate.

The Bergsonian story about the emergence of the biological eye and vision is structured in three acts. In the first act, there are no eyes and no visual world. In the second act, an organ that has the unintended capability for mapping levels of light with directions of bodily movement emerges. As discussed above, at this transition point, ontological expansion occurs and a world of vision emerges. This transition then opens the third act, where a new direction for development is possible and where vision can be improved.

A similar story underlies the GSM short messaging example. Engineers first define a standard that allows short messages to be delivered using the GSM control channel. Then the users invent new unintended ways to use the underlying technical capability, creating a world where 'messaging' becomes a part of emerging social practices. After these new uses are invented, technical progress can be defined as improvements in 'texting', advanced messaging services, and phone interfaces that are optimised for text messages.

In the creative evolution of the eye, before the world of vision emerges and ontological expansion occurs, there cannot be a weak signal of eyes. The transitory moment when a proto-eye gains new meaning as an organ of vision is a creative moment, with no historical precedent. In a world where there is no vision, there cannot be weak signals of vision.

'Weak signals', 'early warnings', and 'seeds of future' thus emerge in retrospective accounts that shape history into prototypical narrative structures. 'Weak signals' of future can often be understood as narrative fragments that are used to compose meaningful stories that make sense of the present as an endpoint of past history. The narrative logic requires that we tell where we came from and where we are going. Making sense of the present thus involves back-casting both the present and the narrative future.

In the case of GSM SMS, ontological expansion looks less radical, as the emerging new social practices can be understood as new forms of already existing practices. In the activity-theoretic hierarchy, the focus of change is on the operational level, as new ways of doing old things. Also here, however, weak signals function as narrative fragments in retrospective stories. The emerging practice is abstracted to a level where there is sufficient stability for continuous stories to be told. For example, text messaging is abstracted as a form of human communication or letter writing. In such an abstraction, of course, that what is truly new in messaging is abstracted away.

In both cases, weak signals can be empirically detected only after the fact, when the future is already here and ontology has expanded. After ontological expansion occurs, we start to receive signals that something has changed and try and fit these disturbing signals in existing narrative and ontological frames. If the fit does not work, we eventually change the framing. At that point, our models of the world also change and we become able to start to gather facts and data about the new phenomenon.

The above analysis opens important questions that deserve further study. On a theoretical level, the lack of predefined ontological blueprints means that weak signals cannot in any straightforward way be interpreted in a realist context, where the 'objects' of the world provide the ultimate foundation for analysis (Hiltunen 2008). Here Nishida's (1987) analysis of the problems of objectification, underlying the more recent work of Shimitzu and Nonaka (Nonaka, Toyama, and Hirata 2008), still represents the state of the art.

Although ontological expansion makes future an unpredictable place, this does not mean that we cannot say anything interesting about the future. It may be impossible to have facts or data that could be used to model imagined futures; we are, however, perfectly able to imaginatively expand current ontologies and tell narrative stories using weak signals that make sense in our imagined futures. In practical terms, we can expand the repertoire of categories and our capability to make distinctions so that we are better able to live in an unpredictable world (Miller 2007).

In strategic decision-making, it is possible that the traditional Ansoffian analysis of weak signals mainly produces fictional certainty that leads to managerial overconfidence and blindness to true novelty and uncertainties. Retrospective narratives make decision-makers believe that future has been predictable before and that they are able to predict the future also now (Bukszar 1999). A potential approach to reduce such misplaced overconfidence is to explicate both the underlying assumptions (Rossel 2009) and the narrative structures (Wright 2005) that are used to make sense of the issue at hand.

As decision-making tends to be inherently a political process, it is often believed that conflict can be reduced by decision processes that emphasise data and facts. The above discussion indicates that such approaches have only limited potential in future-oriented analysis. Future emerges in a periphery where robust facts and standardised interpretations do not exist (Regnér 2003). Instead of emphasising the 'objective' in future-oriented analysis, decision processes and future-oriented analysis therefore should methodologically emphasise domains that are conventionally labelled 'subjective'. Somewhat paradoxically, the mainstream labels of rationality and irrationality need to be reversed if we take innovation seriously. The Bergsonian rationality includes more than the limited rationality that can exist after ontologies are fixed. The Bergsonian claim is that we need a broader understanding of rationality if we want to understand innovation, creativity, and evolution.

Ogilvy (2011) has recently argued that scenario developers and decision-makers have to learn to maintain an agnostic attitude and simultaneously apprehend alternative scenarios. Ogilvy called this the 'scenaric stance' and used Thom's catastrophe theory to illustrate a model where the same values of 'control variables' can be associated with very different outcomes. In this simplified form, full certainty can lead to unpredictability.

Creative evolution and ontological expansion, however, mean that the dimensions of such 'control space' also emerge in an evolutionary process. Methodologically, this means that instead of planning the future or keeping multiple possible outcomes in mind simultaneously, we should be open to the creative potential of the future. As the analysis above indicates, the reality will always surprise us.

Implications for strategy and policy-making

When true uncertainty and ontological expansion are important, formal models rarely provide useful predictions. Innovation expands the ontological space, making previously invisible aspects of the world visible and relevant for modelling. In such a situation, formal models cannot be made more accurate by collecting more data or measuring the observables more accurately. Innovation changes the way the natural system itself needs to be constructed. Ontological expansion means that we do not need a better model; instead, we need a different model.

This creates a challenge for formal modelling. In practice, many future-oriented models are based on time-series data. Such data can be collected only if the ontology and its encodings and the measurement instruments that generate the data remain stable. In general, the data required for formal models are available only in domains where innovation has not been important, and it will have predictive value only if innovation remains unimportant. For example, data on phone calls or callers could not have been used to predict industry developments when short messaging became the dominant source of growth in the industry. Similarly, historical data on national accounts can tell very little about future economic developments, as the data are collected on categories that used to be important in the industrial economies and value production models of the twentieth century. Although many researchers believe that methodologically sound research requires that they stick to well-known and frequently used historical data sets, this approach cannot lead to methodologically robust predictions.

Similarly, reactive what–if models can only provide predictive value if innovation is unimportant. Specifically, there is little reason to believe that conventional 'impact analysis' models could lead to useful insights if innovation matters.

In general, facts exist only for natural systems that have associated measurement instruments and established encodings and decodings between the natural system and its formal model. Facts rarely exist for ontologically new phenomena. It is therefore very difficult to formally model systems when innovation matters. Policies that are legitimised by facts, therefore, are methodologically problematic. Although evidence-based policy-making may be practically useful in the sense that it generates a common frame for policy debates, it may be harmful because it inherently neglects innovation and knowledge creation.

When innovation is important, foresight efforts therefore could more appropriately be located around the problem of articulating natural systems, instead of formulating predictive models. In other words, the focus of future-oriented analysis should be learning, problem redefinition, and innovative construction of new empirically relevant categories, not predictive modelling.

An example here is the problem of formulating ‘grand societal challenges’. Typically, such societal challenges are based on extrapolations of historical trends and thus implicitly assume that historically relevant categories remain important also in the future. For example, ageing may become a ‘grand challenge’ when we assume an industrial age model of factory-based production, industrial era life patterns and health services, an educational system geared towards producing skilled labour, and public financing systems that are based on all the above assumptions. In other words, assuming that the industrial society remains as it used to be, extrapolations from demographic data lead to an unsustainable state. These assumptions, however, are difficult to maintain if we also assume that these societies are transforming towards knowledge societies where innovation is an important economic factor. Simply looking at the demographic predictions, elderly people could well become the dominant productive force in the next few decades, instead of a grand challenge.

If the future cannot be predicted before it happens, foresight requires an imaginative step that resembles the movement of a mountain climber towards the next hold. For purely ontological reasons, foresight cannot be based on reactive models. Models inspired by physics, control theory, or economics are structurally unable to encompass ontological expansion and innovation. They should therefore be used with caution. Foresight efforts can probably best be organised using reflective learning and knowledge creation as their theoretical framework. If innovation is important, we probably should give relatively little weight for trend extrapolations, what–if analyses, and time-series data and instead facilitate creativity and embrace innovation.

Notes

1. Uncertainty, of course, has been a central theme in much of economic theory since Knight. For a critical historical review of key contributions, see Mirowski (2009).
2. Ontological uncertainty has been defined in several different ways by different authors. For example, Lane and Maxfield (2004) distinguished between truth uncertainty, semantic uncertainty, and ontological uncertainty. Ontological uncertainty, for them, is about what kinds of entities inhabit the world, what kinds of interactions these entities can have, and how the entities and their interaction modes change as a result of these interactions. The ontological uncertainty of van Asselt and Rotmans could in this classification be defined as truth uncertainty.
3. The need for text communication, paging, and access to the telex network has already been discussed in the first GSM plenary meeting in Stockholm in 1982 (CEPT-CCH-GSM 1982). The first specification of GSM services, however, lists mobile-to-mobile SMS as an ‘additional service’ (CEPT/GSM 1985). In recent years, both Friedhelm Hillebrand and Matti Makkonen have been described as the ‘inventors’ of SMS (Wallén 2008; Milian 2009). In its present form, SMS emerged only after 1992 when Nokia introduced the first SMS-capable phone.
4. Leont’ev’s activity theory was based on Vygotsky’s theories on cultural–historical development (Luria and Vygotsky 1992). A similar three-level structure emerges when we analyse the communicative meaning of sentences. We cannot derive the communicative meaning of a sentence by adding up word definitions, and we cannot define the meaning

of a word by adding up letters. The letters are used to 'implement' the words, and words are used to say things; the meaning of a sentence, however, cannot be reduced to its constitutive letters. The meaning of activity, similarly, cannot be deduced from observed acts.

5. Cf. Louie (2010), Poli (2010), and other articles in the same special issue of *foresight* on anticipatory systems.

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References

Beck, U., A. Giddens, and S. Lash. 1994. *Reflexive modernization: Politics, tradition and aesthetics in the modern social order*. Cambridge: Polity Press.

Bell, A. 1876. Improvement in telegraphy. In *The telephone and its many inventors*, ed. L. Coe. Jefferson, NC: McFarland, Appendix 10.

Bergson, H. 1983. *Creative evolution* (first edition 1907). Lanham, MD: University Press of America.

Bergson, H. 1988. *Matter and memory* (first edition 1896). New York: Zone Books.

Bijker, W.E., T.P. Hughes, and T.J. Pinch. 1987. *The social construction of technological systems: New directions in the sociology and history of technology*. Cambridge, MA: The MIT Press.

Borup, M., N. Brown, K. Konrad, and H. Van Lente. 2006. The sociology of expectations in science and technology. *Technology Analysis & Strategic Management* 18, nos 3–4: 285–98.

Bower, J.L., and C.M. Christensen. 1995. Disruptive technologies: Catching the wave. *Harvard Business Review* (January–February): 43–53.

Bowker, G., and S.L. Star. 1999. *Sorting things out: Classification and its consequences*. Cambridge, MA: The MIT Press.

Brown, J.S., and P. Duguid. 1991. Organizational learning and communities of practice: Toward a unified view of working, learning, and innovation. *Organization Science* 2, no. 1: 40–57.

Brown, J.S., and P. Duguid. 2000. *The social life of information*. Boston, MA: Harvard Business School Press.

Bukszar, E. 1999. Strategic bias: The impact of cognitive biases on strategy. *Canadian Journal of Administrative Sciences* 16, no. 2: 105–17.

Callon, M., J. Law, and A. Rip. 1986. *Mapping the dynamics of science and technology: Sociology of science in the real world*. Houndmills, Basingstoke: Macmillan.

CEPT-CCH-GSM. 1982. Report from meeting no. 1. T/CCH(83)/9 – GSM Doc 32/83. Stockholm.

CEPT/GSM. 1985. Services and facilities to be provided in the GSM system. GSM Doc 28/85 rev. 2.

Constant, E.W. 1987. The social locus of technological practice: Community, system, or organization? In *The social construction of technological systems: New directions in the sociology and history of technology*, ed. W.E. Bijker, T.P. Hughes, and T.J. Pinch, 223–42. Cambridge, MA: The MIT Press.

Dosi, G. 1982. Technical paradigms and technological trajectories – a suggested interpretation of the determinants and directions of technological change. *Research Policy* 11, no. 3: 147–62.

Engel, P.G.H. 1997. *The social organization of innovation: A focus on stakeholder interaction*. The Netherlands: Royal Tropical Institute.

Feigenbaum, M. 1978. Quantitative universality for a class of nonlinear transformations. *Journal of Statistical Physics* 19, no. 1: 25–52.

Fischer, C.S. 1992. *America calling: A social history of telephone to 1940*. Berkeley, CA: University of California Press.

Fleck, L. 1979. *Genesis and development of a scientific fact*. Chicago, IL: The University of Chicago Press.

Garud, R., and M. Rappa. 1994. A socio-cognitive model of technology evolution. *Organization Science* 4, no. 3: 527–50.

Geels, F.W. 2005. The dynamics of transitions in socio-technical systems: A multi-level analysis of the transition pathway from horse-drawn carriages to automobiles (1860–1930). *Technology Analysis & Strategic Management* 17, no. 4: 445–76.

Giddens, A. 1984. *The constitution of society: Outline of the theory of structure*. Berkeley, CA: University of California Press.

Goffman, E. 1959. *The presentation of self in everyday life*. New York: Anchor Books.

Haken, H., ed. 1981. *Chaos and order in nature*. Berlin: Springer-Verlag.

Haldane, J.S. 1931. *The philosophical basis of biology*. Garden City, NY: Doubleday, Doran & Company.

Hiltunen, E. 2008. The future sign and its three dimensions. *Futures* 40, no. 3: 247–60.
Holopainen, M., and M. Toivonen. 2012. Weak signals: Ansoff today. *Futures* 44, no. 3: 198–205.
Hughes, T.P. 1983. *Networks of power: Electrification in western society 1880–1930*. Baltimore, MD: The John Hopkins University Press.
Jacobs, S. 2000. Spontaneous order: Michael Polanyi and Friedrich Hayek. *Critical Review of International Social and Political Philosophy* 3, no. 4: 49–67.
Knight, F.H. 1921. *Risk, uncertainty, and profit*. Boston, MA: Houghton Mifflin.
Knorr Cetina, K. 1999. *Epistemic cultures: How the sciences make knowledge*. Cambridge, MA: Harvard University Press.
Lane, D., and R. Maxfield. 2004. Ontological uncertainty and innovation. *Journal of Evolutionary Economics* 15, no. 1: 3–50.
Latour, B. 1996. *Aramis, or the love of technology*. Boston, MA: Harvard University Press.
Lave, J., and E. Wenger. 1991. *Situated learning: Legitimate peripheral participation*. Cambridge: Cambridge University Press.
Leont'ev, A.N. 1978. *Activity, consciousness, and personality*. Englewood Cliffs, NJ: Prentice-Hall.
Lewontin, R. 1983. The organism as the subject and object of evolution. *Scientia* 118: 63–82.
Lorenz, E.N. 1963. Deterministic nonperiodic flow. *Journal of the Atmospheric Sciences* 20, no. 2: 130–41.
Louie, A.H. 2010. Robert Rosen's anticipatory systems. *Foresight* 12, no. 3: 18–29.
Luhmann, N. 1990. *Essays on self-reference*. New York: Columbia University Press.
Luria, A.R., and L. Vygotsky. 1992. *Ape, primitive man, and child: Essays in the history of behavior*. Hemel Hempstead: Harvester Wheatsheaf.
Maturana, H.R., and F.J. Varela. 1980. *Autopoiesis and cognition: The realization of the living*. London: Reidl.
Maturana, H.R., and F.J. Varela. 1988. *The tree of knowledge: The biological roots of human understanding*. Boston, MA: New Science Library.
Mead, G.H. 1907. Review of L'evolution créatrice by Henri Bergson. *Psychological Bulletin* 4: 379–84.
Mendonça, S., M. Pina e Cunha, J. Kaivo-oja, and F. Ruff. 2004. Wild cards, weak signals and organisational improvisation. *Futures* 36, no. 2 (March): 201–18.
Milian, M. 2009. Why text messages are limited to 160 characters. *Los Angeles Times*, May 3. http://latimesblogs.latimes.com/technology/2009/05/invented-text-messaging.html
Miller, R. 2007. Futures literacy: A hybrid strategic scenario method. *Futures* 39, no. 4: 341–62.
Mirowski, P. 1998. Economics, science, and knowledge: Polanyi vs. Hayek. *Tradition & Discovery, The Polanyi Society Periodical* XXV, no. 1: 29–42.
Mirowski, P. 2009. Why there is (as yet) no such thing as an economics of knowledge. In *The Oxford handbook of philosophy of economics*, ed. H. Kincaid and D. Ross, 99–156. Oxford: Oxford University Press.
Mokyr, J. 1990. *The lever of riches: Technological creativity and economic progress*. Oxford: Oxford University Press.
Nicolis, G., and I. Prigogine. 1977. *Self-organization in nonequilibrium systems: From dissipative structures to order through fluctuations*. New York: John Wiley & Sons.
Nishida, K. 1987. *Last writings: Nothingness and the religious worldview*. Honolulu: University of Hawaii Press.
Nishida, K. 2012. Logic and life. In *Place and dialectic: Two essays by Nishida Kitaro*, trans. J.W.M. Krummel and S. Nagatomo, 103–74. New York: Oxford University Press.
Nonaka, I., R. Toyama, and T. Hirata. 2008. *Managing flow: A process theory of the knowledge-based firm*. Houndmills, Basingstoke: Palgrave Macmillan.
Ogilvy, J. 2011. Facing the fold: From the eclipse of Utopia to the restoration of hope. *Foresight* 13, no. 4: 7–23.
Oudshoorn, N., and T.J. Pinch. 2003. Introduction: How users and non-users matter. In *How users matter: The co-construction of users and technology*, ed. N. Oudshoorn and T.J. Pinch, 1–25. Cambridge, MA: The MIT Press.
Perez, C. 1985. Microelectronics, long waves and world structural change: New perspectives for developing countries. *World Development* 13, no. 3: 441–63.
Polanyi, M. 1998. *Personal knowledge: Towards a post-critical philosophy*. London: Routledge.
Poli, R. 2010. The many aspects of anticipation. *Foresight* 12, no. 3: 7–17.
Raven, R.P.J.M., and F.W. Geels. 2010. Socio-cognitive evolution in niche development: Comparative analysis of biogas development in Denmark and the Netherlands (1973–2004). *Technovation* 30, no. 2: 87–99.
Regnér, P. 2003. Strategy creation in the periphery: Inductive versus deductive strategy making. *Journal of Management Studies* 40, no. 1: 57–82.
Rosen, R. 1985. *Anticipatory systems: Philosophical, mathematical and methodological foundations*. Oxford: Pergamon Press.

Rossel, P. 2009. Weak signals as a flexible framing space for enhanced management and decision-making. *Technology Analysis & Strategic Management* 21, no. 3: 307–20.
Rossel, P. 2011. Beyond the obvious: Examining ways of consolidating early detection schemes. *Technological Forecasting and Social Change* 78, no. 3: 375–85.
Rubin, A. 1998. Giving images a chance: Images of the future as a tool for sociology. *American Behavioral Scientist* 42, no. 3: 493–504.
Ruelle, D., and F. Takens. 1971. On the nature of turbulence. *Communications in Mathematical Physics* 20, no. 3: 167–92.
Schon, D.A. 1963. *Invention and the evolution of ideas*. London: Social Science Paperbacks.
Schön, D.A. 1983. *The reflective practitioner*. New York: Basic Books.
Schön, D.A. 1987. *Educating the reflective practitioner: Toward a new design for teaching and learning in the professions*. San Francisco, CA: Jossey-Bass.
Schumpeter, J.A. 2005. The analysis of economic change. Reprinted from Review of Economic Statistics, May 2–10, 1935. In *Essays on entrepreneurs, innovations, business cycles and the evolution of capitalism*, ed. R.V. Clemence, 134–49. New Brunswick, NJ: Transaction Publishers.
Taleb, N.N. 2007. *The black swan*. New York: Random House.
Thom, R. 1972. *Stabilité structurelle et morphogénèse: essai d'une théorie générale des modèles*. Reading, MA: W.A. Benjamin.
Tuomi, I. 1999. *Corporate knowledge: Theory and practice of intelligent organizations*. Helsinki: Metaxis.
Tuomi, I. 2002. *Networks of innovation: Change and meaning in the age of the Internet*. Oxford: Oxford University Press.
Tushman, M.L., and P. Anderson. 1986. Technological discontinuities and organizational environments. *Administrative Science Quarterly* 31, no. 3: 439–65.
van Asselt, M.B.A., and J. Rotmans. 2002. Uncertainty in integrated assessment modelling. *Climatic Change* 54, no. 1: 75–105.
Varela, F.J., E. Thompson, and E. Rosch. 1991. *The embodied mind: Cognitive science and human experience*. Cambridge, MA: The MIT Press.
Von Hippel, E. 1976. The dominant role of users in the scientific instrument innovation process. *Research Policy* 5, no. 3: 212–39.
Von Hippel, E. 1988. *The sources of innovation*. New York: Oxford University Press.
Walker, W.E., P. Harremoes, J. Rotmans, J. van der Sluijs, M.B.A. van Asselt, P. Janssen, and M.P. Krayer von Krauss. 2003. Defining uncertainty: A conceptual basis for uncertainty management in model-based decision support. *Integrated Assessment* 4, no. 1: 5–17.
Wallén, M. 2008. Mannen som uppfann sms:et. *Dagens Industri*, May 11. http://di.se/Artiklar/2008/5/11/41905/Mannen-som-uppfann-sms-et/
Whitehead, A.N. 1978. *Process and reality: An essay in cosmology*. Corrected ed. New York: Free Press.
Wright, A. 2005. The role of scenarios as prospective sensemaking devices. *Management Decision* 43, no. 1: 86–101.