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Novelty, Invention, Change

Introduction

In many political and business quarters, in connection with our current sustainability and environmental change dilemma, we often hear that "We must innovate our way out of trouble." However, this can be misleading, or at best insufficient, if it omits to point out that a 250-year period of unbridled and undirected innovation since the beginning of the Industrial Revolution is actually responsible for many of the unintended consequences of the innovation that we presently have to deal with. Those two and a half centuries of near random innovation in every conceivable dimension of the value space of our current path-dependent societal-cultural-environmental system have led to a rapid acceleration of the frequency and scope of invention and innovation as well as serious challenges regarding our environment. Greenhouse gas emissions are only the beginning. As pointed out by Carson (1954), Huesemann and Huesemann (2011) and many others, if we are to avert a major socio-environmental challenge in time, we need to better understand the role of technology, and innovation in particular, so that we can improve our chances to steer invention and innovation in a direction that is more prudent than the one we are heading in.

In the perspective on (material, institutional, and social) coevolution that I outline in Chapters 8–10, technology plays a special role because it mediates between the human mind and the material world around it. All too often, it has been deemed to follow either a material or a societal logic, but I will argue in this chapter that the technological dynamic is all its own, structuring the socioenvironmental interface and the context of the economy. I will do so by discussing the emergence of novelty – the process that has transformed the world from small groups of hunter-gatherers to a global network of nation-states, enabling humanity to grow to more than 7 billion people, tapping an increasingly wide range of natural and human resources, inventing millions of novel tools, and in the process bringing our planet close to complete environmental destruction.

In Chapter 9, I argued that from the dissipative flow structure perspective continued innovation is in effect the ultimate driver behind societal coherence as well as change, because it ensures the ever further dissipation of chaos (the unknown) that is necessary for human organizations to live and grow. In Chapter 10, I described how that process of continual innovation impacts on the coevolution of a society's technology, economy, institutions, geography and much more, engendering a feedback cycle between solutions and problems. But it is now time to discuss the process of invention and innovation itself in more detail.

Importantly, the model of the coevolutionary dynamics that is outlined in this chapter and Chapter 13 as responsible for technological invention also applies to the non-technological sphere – it can be applied to all forms of change in human societies, and has, *mutatis mutandis*, also been proposed for evolutionary changes in nonhuman organisms (Laubichler & Renn 2015).

Technology as "Tools and Ways to Do Things"

From the long-term perspective of the anthropologist and archaeologist, it is unduly limiting to consider technology in the way that is usually the case in contemporary society – as the totality of knowledge concerning material tools and inventions that we currently use, or in the case of a specific technology a subset of the latter. When applied to the past and to other cultures, this perspective is a typical example of what I call looking through the wrong end of the telescope, taking a modern Western concept and projecting it into the past and onto other cultures in the hope of finding the origins of that concept, that way of doing things, that tool, or that technique (van der Leeuw 2014). As most concepts, categories, and technologies have changed through time, it is usually impossible to define their origins with any precision, as they have morphed beyond recognition between the emergence of a novelty and the current shape. As has been discussed in Chapter 6, rather than adopt such an ex-post perspective on phenomena and search for origins of innovations, we have to adopt an ex-ante one, and search for emergence of novelty (van der Leeuw 2014).

In that light we could more advantageously define technology in the broadest sense as ways to do things. In earliest times, most of these were behavioral, whether individual or collective, while material tools were either nonexistent or very simple. Over time, the balance shifted toward increasing complexity of societies' material culture as well as their societal organization.

As we have seen in Chapters 8 and 10, the immaterial domain has always played an essential role in this. It includes the ways in which people organize their thinking and their behavior, the ways in which they interact with each other and with their environment, the ways in which they transform raw materials into tools, and, in the process, adapt their behavior so as to use these tools effectively. But in my opinion it also includes the much wider realm of how societies organize themselves, conceiving of and implementing institutions, rules, laws, and customs.

In this light, the material and immaterial aspects of technologies (in this wide sense of ways of doing things) are, and always have been, closely interwoven and coevolving through time. Indeed, one cannot imagine the adoption of any technology, even a simple one such as the use of fire, without the important changes it triggered in social behavior: consumption of different foods, storytelling around the fire at night, ability to live in colder climates, etc. The same is true of the introduction of agriculture: different foods, different settlement patterns, different subsistence activities, different divisions of labor, etc. And it is also true for very recent inventions, such as the introduction of information and communications technology, of cellphones, etc. Think only of the fact that nowadays we can be much less organized about how we set up a meeting because cellphones can at any time adapt or fine-tune an existing plan.

Objects and Ideas

First, I need to distinguish between invention and innovation. I understand by invention the process of transformation of substance and substantiation of form that is the essence of creation. It can involve only one or a few people or whole teams, and it can apply to material inventions as well as procedural, conceptual (Schlanger & Stengers 1991), even literary ones (Schlanger 1991).

But it is distinct from innovation, the process of introducing and adopting new elements in society, whether new inventions or older ones that are newly introduced in a society because they have become relevant to that society. Innovation generally leads to the modification of behavior, and potentially also of customs, institutions, and other organizational aspects of a society.

Technological invention and innovation occur in the interface between the realm of phenomena and that of ideas. Ideas are instantiated in some material or organizational form, and when introduced in that form in society give rise to new ideas and new instantiations. I must therefore outline my perspective on the relationship between the respective realms of ideas and things.

Since the Enlightenment, in the western intellectual tradition, we mostly accord phenomena and objects (facts) a status that is independent of our cognitive capabilities. This is expressed by a phrase attributed by my history professor at the University of Amsterdam to the nineteenth-century historian Ludwig von Ranke: "Opinions may change, but facts remain." This position has of course come under scrutiny from the cognitive sciences, which emphasize that the way we understand phenomena is culturally, emotionally, and socially impacted and can vary greatly between individuals. Yet, for example in physics and the natural sciences, most phenomena and processes are still deemed to lead an existence independent of our cognition, and research in these disciplines is generally thought to be aimed at "discovering" them. This perspective has in many instances been extended to the study of technology: the material aspects of various ways of doing things have in our modern minds gained the status of facts, whereas the ideas that have led to their implementation have been given much less attention.

In a similar vein, in economics, resources are often seen as essentially natural, and thus existing outside the social realm. I would argue that, on the contrary, resources do not exist as such unless they have been identified and integrated in society's ways of doing things – until they have been recognized as valuable, and processes and procedures have been developed to socialize them, making them an integral part of a society's flow structure and value space. They derive their value from that integration, which gives them a role in society, and which (re)shapes society in ways that integrate them.

In both instances, the role of the realm of ideas (including values and norms, see Chapter 17) in instantiating our relationship with the environment has been overshadowed by that of the material realm. This then raises the question of how far our ideas are shaped by observed phenomena or how, vice versa, our conception of reality (the world out there) is shaped by our ideas. Clearly, this is a chicken and egg question, and unsolvable. It is not really important for us here, except for one aspect: the relative lifespans of phenomena and ideas. In the traditional, positivist, approach, this was represented by the quote attributed to Ranke: facts outlive ideas. But from the perspective proposed in this book it is the other way around: the fundamental conceptual structure of tools for thought and action, and thus ways of doing things outlives objects and technologies, even if in detail they are modified. Ideas determine how we look at things, what we see, and what we do not see. Phenomena are poly-interpretable, depending on which of their many dimensions are observed by our cognitive apparatus, which is – as we have seen in Chapter 8 – very limited in its dimensionality and differs greatly between people, groups, and cultures, depending on the process of socialization and learning that they have undergone.

Human perceptions are shaped by information processing that is, as Luhmann argued (1989), self-referential within any one society or culture, so that different aspects of our perceptions reinforce each other into a coherent system. This coherence is reinforced by the overdetermination of our observations by past experience (Luhmann 1989, 35; Atlan 1992), which tends to suppress out of the box change and promotes a long lifetime for the values and perspectives that characterize a society or culture.

The Presence and Absence of Change

Before I drill down into the process of novelty creation itself, we need to consider the relationship between change and its absence in our western intellectual tradition. Girard (1990) describes elegantly how, over the last three centuries, the focus in western (for which read European) culture has shifted away from stability toward innovation, as part of a shift from seeing the present in the context of the past to seeing it in the context of the future. As a result, much of our intellectual focus is currently on explaining novelty and change, rather than explaining stability (the absence of change). It seems to me that it is worth questioning this implicit assumption of stability and the need to explain change. One could just as legitimately, with Heraclitus of Ephesus, argue that change is ever-present in open, living systems, and that therefore stability needs to be explained. One would then ask what is responsible for the absence of change in living, open, socioenvironmental dynamics. I conclude that as novelty cannot be perceived without stability, the two concepts are inextricably interwoven, and we must look at their interaction.

It is one of the intriguing advances of genomics that the same regulatory mechanism that is responsible for change is also responsible, under certain conditions, for its absence. Could we conceive of a similar regulatory mechanism in society? Or to put it in more technological terms, what might be responsible both for the maintenance of technological traditions and for the introduction of novelty into them? To begin answering this question, we need to adopt a model of the ways in which a technological tradition is dynamically articulated between the ideas and practices of its practitioners and the physical, chemical, mechanical, and other characteristics of the natural world. And to understand this dynamic articulation, we must apply a combination of an objective perspective on the realities of the physical world and a cognitive perspective on the ways the inventor deals with them.

Perspectives on Invention

It is my contention that the study of invention has been hampered by a confusion between the perspective of the scientist, who looks from the outside at the process of invention, and the perspective of the actor, who is involved in the process. These perspectives are fundamentally different and must be distinguished and applied in conjunction, because in scientific practice, of course, both are interacting; it is in that interaction that invention occurs. The person I here call the scientist usually has a tendency to explain phenomena, procedures, and the conditions for and results of actions in terms of cause-and-effect, whereas the person I here designate the inventor thinks in terms of multiple options for actions and their intended and unintended consequences. The former practices in effect an ex-post perspective, explaining results, whereas the latter's point of view is ex-ante, focused on the challenges of constructively juggling the many parameters involved in creating novelty.

Rather than try and achieve clarity and certainty by reducing the number of dimensions brought to bear on the challenge at hand, as the scientist usually does, the actor thinks in terms of ambiguities, uncertainties, possibilities, probabilities, and experiments, in the process enhancing the number of dimensions taken into consideration. When asked to explain certain phenomena, the actor does so with the totality – or at least the relevant parts – of the complex system in mind that relates to the phenomena in question, and will therefore usually be able to identify several chains of cause and effect that could possibly result in the phenomena in question, whereas the scientist tends to focus on one explanation only.

Invention in Economics

Since an important focus of our coevolutionary approach is the role of innovation in society, and the economy is in many ways the place where that articulation takes place, I will begin with a very brief historical reexamination of some milestones in the economic study of invention and innovation, from Schumpeter via Usher and Rosenberg to the present.[1]

Schumpeter's Focus on the Effects of (Exogenous) Technological Change

Most early twentieth-century mainstream economic theory considered technological change to be exogenous to the economic system, and thus not an object of economic analysis.

Schumpeter's theory of economic development (1934), on the other hand, conceives of invention and innovation as entrepreneurial activities, and focuses on innovation as an act of investment that requires the *ex novo* creation of means of payment by credit institutions. The entrepreneur selects innovative projects that offer profit-making opportunities (1939),[2] and this allows him to obtain funding from financial institutions. But the profit disappears as soon as an innovation is adopted by others. Schumpeter remarks that innovations appear in clusters (1934; 1939). According to him, this happens because a swarm of entrepreneurs will spread the innovation into related industries. This could explain the cyclical behavior of the economic system, because the interest in the new domain may cause ongoing projects to be crowded out by new ones.

Usher's Cumulative Recombination Synthesis

However, one cannot understand innovation without fundamentally understanding the technology itself, as well as the economic and social dynamics that constitute the context in which it operates. It is essential to widen the scope of innovation studies accordingly. Usher moves an important step in that direction. According to him (1929), novelties are not the product of individual creativity, but of the cumulative actions of many individuals operating in a given historical, social, and institutional context with a certain stock of available knowledge.[3] Invention unfolds in a sequence of four stages:

- The first is the perception of a problem, where a certain generally accepted framework is recognized as incomplete and unsatisfactory;
- The next, the setting of the stage, defines the contours of the problem and explores its various dimensions by means of a trial-and-error approach;
- In the third, an act of insight takes place, which produces a solution to the problem;
- In the fourth, a critical revision of the accepted framework leads to the adoption of the innovation.

The pivotal stage is, therefore, the insight. Rather than from intuition or creativity, Usher argues that insight results from a process that is determined by the intrinsic properties of the context within which the solution is explored. This does not mean that this process is propelled by necessity. Perceptions play a role, and chance also plays a part by introducing unforeseen and unpredictable elements. Invention is therefore characterized by discontinuities that are crucial in the transition to a new state of the system, as well as by a progressive synthesis that connects one stage to the next. Insight emerges when various behavioral matrices are associated (Koestler 1964). Once a solution has been found, we no longer separate what we have joined, and the result seems the logical consequence of the premisses involved. But we do not know which things have *not* been taken to their logical consequence.

Usher's vision underlines three important aspects: a particular act of insight may not lead to the solution of the main problem to which it is directed; chance is part of a pattern of events that unfold in a certain sequence; and finally, the choice of the solution to be adopted depends on incentives and constraints that are not only technical but also social, economic, and institutional.

Rosenberg and the Drivers of Technological Convergence

Various scholars, such as the anthropologist Leroi-Gourhan (1943, 1945) and the philosopher Simondon (1958), have noticed that technological change is not random; there is an inherent tendency in the evolution of such change. Economists have initially assumed that such tendencies in technical change are driven by economies in production, but that does not explain the specific sequence or the timing of innovations. Inspired by

Hirschman (1958), Rosenberg (1963, 1969) argues that "complex technologies create internal compulsions and pressures which, in turn, initiate exploratory activity in particular directions" (1969, 111). Two important features of the innovation process are technological imbalances and compulsive sequences. Technological imbalances (which we might nowadays call bottlenecks) often occur in the production process in individual firms or vertically integrated industries. They favor change when initial innovations do not only affect a single stage of the production process but also require modifications in other, preceding or following, stages.

Such technological imbalances occur particularly often in the transfer of technologies from one industry to another (spillovers) for three reasons: because the need to overcome them steers research in particular directions,[4] they often lead to the creation of new, specialized production tools for particular products, and they widely spread a wealth of new, specific technical knowledge. They can thus lead to technological convergence.

Uncertainty can be a trigger for innovation (such as when innovations are adopted to circumvent inputs whose availability is subject to unpredictable variations), but it can also slow down the development and diffusion of new techniques (Rosenberg 1983, 1994). Uncertainty is therefore a key element in the analysis of the innovation process. A central role is played by the social process through which innovations emerge and by the cognitive realm; a process where uncertainty influences both the ways in which the actors behave and the direction and timing of the innovation process.

Arthur: The Observer's Perspective

But to study invention and innovation we must adopt a generative approach; from a perspective that moves upstream against the flow of time, we must move to one that moves downstream with the flow of time. The Complex Systems approach, with its emphasis on emergence, does that to some extent, and it is therefore not surprising that two of the most complete recent attempts to look into innovation have that approach at its origin.

The engineer and economist Arthur (2009) sees a technology as a construct to capture natural, behavioral, social, organizational, or other phenomena for one or more purposes. This does not only include technologies in the traditional sense, but also business organizations, legal or monetary systems, contracts, etc. Technologies are not standalone objects, but instantiations of more general patterns of organization and transformation that can be combined or otherwise reorganized. First, every technology is organized around a central concept or principle that harnesses a phenomenon to fulfill a certain (set of) function(s). Secondly, that principle is instantiated in the form of (physical or social) components that, together, constitute the central assembly of the technology. Thirdly, that central assembly is usually supported by other technologies whose role is to permit the assembly to function appropriately. Fourthly, all technologies are part of a multilevel recursive structure, consisting of technologies within technologies all the way down to their elementary parts, and they are themselves embedded in a hierarchy of organizations of a social, institutional, and/or economic nature that they help function appropriately.

Arthur views the long-term evolution of technology as a kind of bootstrapping from a few simple technologies (such as stone tools) to numerous complex ones (e.g., nuclear reactors, the Internet), driven by the capture of unknown phenomena that can be harnessed into new technologies and the recombination of existing simpler technologies into more complex ones. The capture of unknown phenomena leads on the one hand to cascades of new scientific discoveries and on the other to relatively rapid explosions in innovation within specific domains (groupings of technologies that work naturally together).

Arthur (2009) distinguishes four levels of innovation: (1) new solutions within given technologies, (2) novel technologies, (3) new domains of technology, and (4) the overall technology of a society.

1. New solutions within given technologies. Every technological realization is a human creation involving problem solving, organization, and action, and is implemented by orchestrating the different component parts of the creation (including ideas, tools, and the like) to exploit their advantages and avoid or minimize their drawbacks. This is the process of design, and it entails making sets of choices that reflect the relationship between the realm of ideas and the material and/or social reality that gives birth to the designed object. To understand that relationship, we must evaluate the choices made against the options not chosen in every step of the creative process. Theoretically, for most designs, the number of options is huge. But in practice, many of these are excluded by physical or other constraints. The cumulative effect of the (small) percentage of novel theoretically possible options that are instantiated moves a technology along in certain directions. Coherent sets of such options may become standard building blocks – and may easily replace older

modules that no longer meet the needs of the times. How the blocks emerge is in many ways path dependent on a combination of chance events and processes, so that the solutions implemented are not necessarily optimal.

2. Novel technologies are technologies that use a different principle to deal with the problems at hand. Their emergence is shaped by a conjunction of social needs, experience outside the technological domain they normally apply to, conditions that favor risk-taking, and exchange of ideas and knowledge between individuals. But they come into existence when the needs are conceptually and physically linked with a new, exploitable (set of) principles and their effects. Whether in science or in technology, the core of innovation is this process of linking problems and principles. It entails mental association between the two via a mapping of their functionalities onto each other.
   - Arthur distinguishes three phases in a technology's life span: (1) 'internal replacement' (replacement of borrowed or otherwise non–optimal parts of a technology by better suited ones), (2) 'structural deepening' (adding subsystems to the system to focus, stabilize, and/or improve its performance, or to increase control over it), and (3) 'lock-in and adaptive stretch' (stretching the technology's performance after it has become so embedded that fundamental change is no longer on the cards). Eventually the principle, now highly elaborated, is strained beyond its limits and gives way to a new one that is initially simpler but in due course is elaborated, so that the cycle begins anew. The overall process is not dissimilar from the *Structure of Scientific Revolutions* (Kuhn, 1962).

3. New domains of technology. Often, technological domains coalesce around a central set of principles and tools that are initially developed in other, established, domains. At this stage, large parts of that new toolbox (enabling technologies, understanding of some of the dynamics) are still missing. As it grows, so will awareness of the missing parts, and research will plug the gaps. Once that has advanced enough, an industry will start to grow, starting with small companies. The challenge for them is not so much the development of new products as the triggering of the cultural and social restructuring that is needed to allow the insertion of the domain into the fabric of society. If that succeeds, the domain may spawn new subdomains, starting the cycle anew. When the new domain encounters opportunities to expand, it must adapt both itself and

the relevant part of society to the new functionalities involved. We may view this as the kind of mutual learning that occurs when different cultures interact (acculturation).

- Rather than the identification of new principles, it is this collective learning and implementation process that sets the pace for the evolution of a technology. Among its many constraints are the nature and lifetime of investments in the old, as well as the new, technologies. The replacement requires, moreover, that the economy transforms itself to take the new technologies into account – in that sense technological domains determine epochs in the economy, while the changes in economic structure determine the time involved. All this makes for a very slow process.

4. The technology of a society. In the bootstrapping process, finer and finer distinctions are made over time between different functions and different ways to deal with them. As the number of technologies increases, so does the number of combinations that are possible between them. As technologies emerge in society, they weave a web among them that links principles, implementations, functions, artifacts (including organizations), materials, and intellectual and material tools in ways that are adapted to the way of life and the worldview of the members of that society. The economics of this process heavily impact on its ultimate structure. In that process, one can distinguish discrete – but not necessarily sequential – steps: (1) entry of the technology as a new node into the active collection of technologies; (2) it becomes available to replace existing technologies or components; (3) it sets up new opportunity niches for supporting technologies and organizational changes; (4) older technologies fade from the collective, and their needs are dropped; (5) the novel technology becomes available as a potential component in further technologies; (6) the economy – the pattern of goods and services produced – adjusts to this, including costs, prices, and technologies.

- In certain cases, once a threshold is crossed, this leads to cascades of destruction and creation.[5] It is important to be aware that this evolution is neither completely random nor in any way predetermined. There are moments in which the evolving technology "chooses" and other times at which it simply advances on its path. That has important consequences for the potential to steer technological evolution - there must be developments we can to some extent predict (at least over a limited time horizon) and moments we cannot.

The importance of the economy in all this leads Arthur to reformulate its role and structure in a very interesting way. Rather than see it as a system of production, distribution and consumption of goods and services, he takes a wider definition: “the asset of arrangements and activities by which a society satisfies its needs” (Arthur 2009, 230), and rather than see the economy as the context or container of its technologies, he sees it as constructed from its technologies. This fundamentally changes the balance between economics and technology studies in understanding innovation. Technologies constitute and shape the economy’s structure. The economy emerges from its technologies – and thus continually forms and reforms as its technologies change. As the technology builds, it transforms the structure of the economic flows and decisions, and the transformed economic structure then enables changes in the technologies – the bootstrapping that we have seen for the technology actually also transforms the economy. And in the process, this bootstrapping changes the structure of society, or at least of many of its institutions (such as its banks, but also its ethics, laws, governance, etc.) (see Padgett 1997, 2000).

In conclusion, Arthur offers a first plausible theory of technology, although not (yet) one from which metrics of innovation can be derived. The importance of that theory is that it actually deals with the second order dynamics in which most innovations studied are embedded – it deals with the change of change, both in technology and in economics. It inverts the relationship between technology and economy, and thereby the focus of research on innovation – rather than distilling from economic data policies and measures to improve innovation it argues for the reverse, and whether that will in the end be correct or not is not as important as the fact that we can begin to build on his work to construct a theory of innovation that fuses the technological and economic dynamics into one, and extends both to encompass all forms of human-engendered organization.

Lane and Maxfield: The Innovator’s Perspective

Lane, Maxfield, and their collaborators (1997, 2005) focus on how people view, conceptualize, and act in a reflexive way between their known past and their unknown future. In that interaction, ontological uncertainty plays an important role, the uncertainty that is the result of simply not knowing what the future will look like or bring. At the level of the individuals involved, reducing that uncertainty (which depends on the actors’ beliefs about the kinds of entities that inhabit their world, about the interactions among them, and about how these interactions might change) in any firm and specific way is the wrong thing to do. But by relating past, present, and future in narratives that create a semblance of order, yet are easy to change, exploration of futures is both enabled and to some extent controlled. Such narratives allow the actors to back into the future. The (reduced) ontological uncertainty involved both allows for invention and limits the total range of inventions likely to emerge. The narrative thus creates a kind of path dependency for invention. An interesting aspect is that there may be a relationship between the extent to which the past is flexible rather than fixed in the actor's mind (which might facilitate the changeability of the narratives) and the facility with which an actor can explore new ideas.

At the level of the local agent network, a similar role is played by the attributions of the actors to the other agents in the network: what are the qualities, functions, relevant attributes of different actors and relationships that are deemed relevant, and how do these relate to one another? Invention is essentially the generation of new attributions (new, different ways to look at an artifact or process; ascribing a new function to it, for example, or suddenly noticing another way to use it, or an aspect of it that one had until then overlooked). Such attributions arise in generative relationships among agents.

Though it is not possible to pinpoint the new attributions that may emerge one might, according to Lane and Maxfield, be able to assess the generative potential of a relationship by considering five characteristics: (1) aligned directedness (degree of alignment of the group of agents toward a particular objective), (2) heterogeneity among the agents, (3) mutual directedness (extent of focus on reciprocal relationships between the agents), (4) appropriate permissions (relevant opportunities for communication among agents), and (5) opportunities for action. These can be seen as the basis for relevant metrics concerning the inventive and innovative potential of the interaction between the agents.

Finally, as Lane and Maxfield move from the local corner of the global network in which inventions may occur to the network as a whole, their concern changes again (and so do the concepts involved). The network is seen as consisting of established competence networks and scaffolding structures put in place to construct new competence networks. The latter are governed by their conventions, both explicit (membership of a professional society) and implicit (a shared way of using expressions and abbreviations). The dynamics between these two consist of search (from a point in the scaffolding network) into the various potentially relevant competence networks, in order to identify potentially alignable members of the scaffolding structure, information dissemination (to the potential new members), interpretation (by the latter), and channeling (using the scaffolding structure to channel activities that may reinforce and expand it).

All in all, Lane and Maxwell's work presents a phenomenology of invention and innovation processes around the concept of ontological uncertainty about the future. Such uncertainty is endemic because the transformation that is brought about by the innovation does not correspond (or only very partially corresponds) to the intentions of the individual agents. Narratives, generative relationships, and scaffolding structures all work to enable agents to cope with ontological uncertainty, in part by temporarily holding it at bay (in narratives), in part by offloading, segregating, and channeling it into special-purpose venues where interactions are highly controlled. At the same time, ontological uncertainty is uncovered, explored, and exploited in special relationships between agents.

But the work also introduces three theories of relevance to invention and innovation studies: the narrative theory of action, the theory of generative potential, and the theory of scaffolding structures. It is our opinion that these together provide a highly relevant and effective toolkit to study the process of organizational change induced by invention and innovation. I cannot here enter into details, but have to refer the reader to the publications mentioned.

Open Questions

Which of the thus far unanswered questions may we expect to be able to answer by applying this approach? As previously mentioned, the measures used in economics to identify invention, inventiveness, innovation, and related phenomena are predominantly a-posteriori indicators. Studying statistical correlations between them helps us to understand the context of invention and innovation, and which conjunction of variables influences the processes, but not how invention and innovation happen. Combining the approaches of Arthur with those of Lane and Maxfield lays the foundations for studying just that. We could then begin to develop the correct metrics to assess change, and then also to impact the process itself.

The distinction between replicative and innovative entrepreneurship is firmly established in the literature. But what interests us is how a non-inventive entrepreneur might become an inventive one. Knowing that would help us promote innovative entrepreneurship in a more focused way, create more conducive social, legal, and economic contexts, and adapt our educational strategies, for example.

Moving a level up, to the community, we remark that the study of innovation has enabled us to characterize at least loosely what makes a community innovative (see Florida 2002), but does not enable us to understand the process by which that community has acquired such an innovative culture. That would be particularly relevant to understanding our current western economies, but also how in parts of those (for example in the financial and information technology domains) excesses are triggered (other than through simple greed).

At all three levels, one important aspect of our work will (again) be to try and evaluate choices made against options not chosen. What is the weight of a particular technical choice in the development of an invention? What is the impact of choosing to develop it for a particular purpose and not for another? How about choosing among one of the many options open to create scaffolding structures? What was (were) the decisive factor(s) in developing an innovative community, and what is the impact of that (those) factor(s) on the form that community takes?

Combining these ideas would enable us to map some of the processes leading all the way from the emergence of the ideas and decisions that engender inventions, via the network dynamics responsible for their spread into the wider world, to their implementation in different contexts, and to their eventual unanticipated consequences for sustainability and the challenges these pose.

Improved understanding of that chain of processes and events should ultimately enable us to modify it in ways that deal more effectively with the initial challenges and minimize or mitigate the unanticipated consequences, so as to ensure improved sustainability of the technology, the economy, and more widely the socioenvironmental system. In the following sections, I will try to illustrate how these ideas might be used in practice.

The Inventor and the Context: Niche Construction

Material innovations play out at the interface between a society and its natural environment. At that interface, techniques do not follow either the logic of the society or that of the environment. Though they relate to both they are not determined by either. To understand the logic involved, we need to adopt a non-determinist approach, in which the role of the maker/inventor's ideas and choices is at the core of our reasoning, and we focus on how it articulates with the outside, material, world. As we saw in Chapter 10, that articulation plays out in the interface between solutions and challenges.

The *chaîne opératoire* approach first introduced by French anthropologists and archaeologists has greatly advanced our understanding of the procedures by which artifacts are created (van der Leeuw 1976, 1993; Lemonnier 1992, 2012; Boëda 1994, 2013; and others), and has drawn our attention to the cultural context of creation. It aims to reconstruct the process of making, from the traces left by the makers' actions on the objects made to the actions that were responsible for these traces. By reconstructing the sequences of action whereby artisans (and users) act on matter in the production (and consumption) of things in order to deal with challenges they face, this method encourages a thoroughly relational, systemic outlook on materials and artifacts. Every object is the outcome not only of, for example, the choice of raw materials, but also how the materials were prepared, how the artifact was then formed, and finished – and how any one choice in the sequence impinges on the others. Hence one begins to see the finished artifact not as some fixed entity, but as a kind of emergent stabilization from among a field of forces that are in some tension with one another – change a pottery firing technique and one may have to change the clay; change a decorative motif, and a different pigment may be required.

But the *chaîne opératoire* approach does not put this process in a wider, equally dynamic context that might help us understand how change occurs in any specific manufacturing tradition. To achieve that, as Knappett et al. (in press) have argued, we need to move from ontology to ontogeny. In thinking about actions, and the humans performing those actions, the next step is to contemplate:

1. Which dynamics may be responsible for variations in the instantiation of a technological tradition, leading to invention and innovation within such a tradition?
2. Given such variation, how do societies maintain a particular manufacturing tradition?

But the two questions constitute a tangled hierarchy (Dupuy 1990), so one could therefore also invert them and ask:

1. How do societies dynamically maintain a particular manufacturing transition?
2. How does the dynamic involved in maintaining a tradition nevertheless allow for the emergence of novelty?

Among the useful concepts that a comparison between the emergence of novelty in biology and in society offers us is niche construction (Odling-Smee et al. 2003). Laubichler and Renn (2015) include this concept in their extended evolution model that emphasizes the links between the internal dynamics of a system and those that create its environment and link both. It reflects the idea that we cannot realistically represent or study invention or innovation without taking into account the fact that it occurs in, partly shapes, and is shaped by, its context. In the process, inventions and innovations create a dependency relationship with their niches in the wider context, and if, for some reason or other, that context changes, the invention may well disappear or be transformed. Conversely, if the innovation is no longer produced, the niche will disappear.

When applying this concept of niche construction to our study of technological invention, and in particular to the relationship between the inventing actor and the context in which invention occurs, we should articulate our perception – which should be as complete and unbiased as possible – of the different functions, materials, techniques, etc. that constitute that context in the world out there with a perspective on that context representing the actor's subjective point of view. That perspective is always partial, biased, and part-driven by social, cultural, and other factors external to the material context of innovation, and its object of study is how the maker's perception articulates these factors with the material conditions of manufacturing.

The stage for this articulation is the interaction between the objective context of manufacturing and the subjective map the inventor has of it. In the process, the external (natural and social) world and the internal (perceptual) world of the actor (partly) shape each other. Over time, this engenders a coevolution that in turn shapes the wider context of invention and innovation in what we call a technological tradition. In this coevolution, each and every technological choice, once it is made, limits the total option set of future choices and generates its own set of unintended consequences, eventually leading to new solutions. The same is true of every social, organizational, and institutional choice made.

The domain in which material and procedural inventions occur, which we could call the technosphere, thus has a logic all of its own, which does in part shape, and is shaped by, the path dependency of a society around its evolving technology.

There are (at least) three levels of knowledge involved in shaping that coevolution:

1. The slowest to change is the collective knowledge that is shared between the members of the community involved. Change at this level involves changing the worldview of the community, its habitus, its approach to technology. The main barrier to such change is that the perspective of the community is limited by the things it has never thought about and which it therefore has no way to describe, analyze or conceptualize. Breaking through that barrier is itself a major invention/innovation. But there can also be conscious social barriers, for example through the protection of intellectual property rights.
2. At the level of the individual one has to take tacit knowledge ('know-how') into account, which has either been subsumed under more conscious conceptual knowledge and customs or resides in the physical, neuro-muscular behavior of the human body. It is difficult to acquire, requiring substantive and often long apprenticeship, but it is also difficult to change as it is not embedded in our conscious memory but is exercised as routine movements and actions.
3. But the individual also has conscious knowledge ('know that'), which is subject to conscious learning and is therefore the easiest and quickest to change. It actively involves the conscious mind, planning and changing behavior. Yet one must remember that such conscious knowledge is also limited by its boundary with the unknown – those processes, questions, and challenges that one has never thought about. It is in this domain that inventions are born most easily.

Looking at the conceptual aspects of techniques in this manner, as anchored in the mind rather than constrained by natural resources and the technological environment, makes a plausible argument for the fact that novelty is limited by the way in which traditions are anchored conceptually and in practice. But how might the same conceptual dynamics engender change? To answer that question, we need to look into the ways in which the practitioners of technologies articulate their relationship with the outside world, and in particular we need to give a central role to choice. Humans are making choices at every step of the way in the manufacture of even the humblest artifact – which means that technologies are mindful and full of intent (and as stated, these choices are typically interdependent as well). That a technological approach then becomes, in this recognition of choice, inherently cognitive (though not by default cognitivist) is worth emphasizing, because it is quite distinct from a materialist or biological outlook.

Creation, Perception, Cognition, and Category Identification

I have already cited the eminent anthropologist Roy Rappaport, who said in a lecture series I attended at the University of Michigan in Ann Arbor in 1977 that "Creation is the simultaneous substantiation of form and information of substance." It involves a back and forth between mind and matter in which a form (an idea) is given shape in the material world. That process is iterative at two levels. The most evident of these is the fact that the maker begins with an approximate idea of what she or he intends to make, and during manufacture both corrects that idea and fine-tunes the product made. But there is also a deeper level in which the process of creation is iterative: that of defining the categories to be distinguished by the maker in the process of making. At that level, the iteration involves the interaction between perception and cognition in the mind of the maker. Modern cognitive science is in the process of learning how this works in the mind, but as a noncognitive scientist I do not pretend to be able to look at this process at that level. Rather, I would like to use the simplified model of category creation that is summarized in Figure 9.1, of which the basic idea is that the process of relating categories to observations is dependent on which of the two serves as a referent.

To summarize, when a concept is being generated, this is a process of comparing an idea as a subject of exploration with phenomena that serve as referents. In such a comparison, the emphasis is on similarities. After a while, the concept is established because one has a good sense of the phenomena that might belong in the category, but not yet of the phenomena that in the end might not. To gain the latter insight, the direction of the comparison is reversed – the category becomes the referent and the phenomena are compared to it. In that process, the mind emphasizes the dissimilarities between phenomena and concept, so that in the end one knows both what belongs and what does not belong in the category.

We have seen how this description of the process of categorization leads one to distinguish between open categories (where one knows which phenomena might belong but not yet which do not) and closed categories (where one knows which phenomena do belong and which do not). It seems to me that this description does indeed summarize for our purposes what goes on in the creative process, leading to the categories adopted from among the many potential ones that the creator does indeed understand and actively exploit in thinking about the manufacturing process. But of course it ignores a number of other factors, such as the emotional ones that are increasingly recognized as important in category formation and decision-making.

On the basis of this schema, one can distinguish three different cognitive spheres or cognitive spaces that are simultaneously present in the mind of a creator during manufacture:

- A certainty sphere that is fully cognized, which is made up of the closed categories in the mind of the maker of (not only material) artifacts, so that he or she knows exactly what is what and has a fixed idea on how to proceed;
- A possibility sphere, which consists of the open categories in the mind of the maker, where the latter is still to some extent undecided and therefore flexible in his or her interactions with matter;
- A problem sphere, consisting of the domain for which there are no categories (yet) in existence, and which therefore is that of the unknown and dimly perceived but unsolved challenges, about which the maker has no idea at all.

If we next look in some more detail at how the maker deals with the problem sphere, we need to take into account that the human perception of the present iteratively relates an assumed past to personal experience and projects the resulting vector into the future. In other words, there is an interaction between perception from an a priori point of view, which opens opportunity for variation, and perception from an a posteriori perspective, which limits variation – the former is focused on emergence, on novelty, and on possibilities and probabilities (opening categories), while the latter is focused on origins, on tradition, and on causality (closing categories). It is in that interaction that invention takes place.

How Are Technical Traditions Anchored?

Next, it is interesting to look at how this interaction engenders both stability and change. Based on a comparative and detailed study of a wide range of past and present pottery-making traditions from different parts of the world that produce highly similar, globular pottery I have in an earlier publication (van der Leeuw 1993) focused on the importance of choice in studying creation, including manufacturing. That has led me to conclude that any approach to exercising a technique is anchored at a minimum of three different levels, in increasing order of flexibility and opportunity for change.

1. First of all there are the temporal, spatial, and functional conceptions of the objects to be made, anchored in the minds of the makers' community. These shape the topology of the objects to be created, their partonomy (the relationship between a whole object and its parts), and the sequence in which the creators create their products. In most technical traditions, all three of these are deeply anchored in the collective as well as the individual (tacit and conscious) knowledge of the individuals involved, and not likely to change. They constitute the domain of the closed categories and as such anchor each individual technical tradition in its own way. New procedures to be introduced are generally such that they take the existing conceptions of topology (space), sequence (time), partonomy, and function into account. Not doing that would make innovation extremely difficult.
2. Next in my overall scheme of things are the executive functions, the tools and techniques acquired to instantiate objects that meet the existing topology, partonomy, function, and manufacturing sequence. Importantly, these executive functions include tools and the ways in which these tools are used. Executive functions are part of the possibility space in the maker's mind. They are generally anchored in both the unconscious and the conscious knowledge of the person practicing a technology. Change in these executive functions will initially involve the conscious knowledge of the maker who experiments with the effects of a change, but once the usefulness of a particular change in executive functions has been established, with time, the tacit knowledge-base will also be involved, through longer-term practice of the actions concerned, so that they become anchored in the musculo-skeletal memory of the practitioner.
3. The third level is that of the choice of raw materials and other components of a technology, including their nature, their quantity, and their preparation. This domain is also part of the maker's possibility space. Except in very constraining and limiting environments, these can be varied the easiest and adapted to changes in executive functions. Often, their adoption depends on the availability of parts, materials, etc. of other technologies. But the choices are made according to the ways in which the practitioners of a technology articulate them with their conceptualizations by means of the executive functions they adopt. That articulation is itself an interactive process.

I am positing that invention is part of the process that creates new categories in interaction between knowledge and data (closed and open categories) that occurs between the certainty sphere (closed categories), the possibility sphere (open categories) and the problem sphere (potential categories), and that the degree of novelty depends on the extent to which each of these spaces is involved.

The Locus of Invention

In practice, this interaction occurs between the (externally defined) context of the manufacturing process (the niche in which invention occurs), which encompasses both sociocultural (customs, institutions, economy, etc.) and material (resources, existing components and technologies, etc.) elements of that context, and the (internally defined) perception the creator has of those components. The articulation between these two is at any time a question of choice, but the choice is not (as is often assumed in the black-box model of novelty creation that relates input and output without looking at the dynamics occurring inside) random or unlimited. Choices are always limited by the reality and the perception of the niche to which the choice relates.

As a starting point, we must therefore attempt to characterize the niche in which a practitioner of a certain technology operates and the total set of contextual variables that might impact on the choices that the individual can make, whether inventive or not. Once that is done, we have to see if we can identify among that set those variables that are actually perceived as sufficiently important to be taken into account in the practitioner's approach to practicing the technology.

In Chapter 13, I have chosen the (admittedly relatively simple) example of manual pottery-making to illustrate the invention dynamic, relying on my knowledge of both the external and the internal perspectives of the context in which that craft is practiced by pre-modern potters (van der Leeuw 1976, 1991, 1993, 1994a, 1994b; van der Leeuw & Pritchard 1984; van der Leeuw & Torrence 1989; van der Leeuw & Papousek 1992; van der Leeuw et al. 1992).

NOTES

1 The first part of this examination is based on a very gracious, unpublished, contribution of Margherita Russo (University of Modena, Italy) to a study into invention and innovation funded by the Kaufmann Foundation that I directed

at ASU between 2007 and 2011. If there are any errors, of course the fault is mine.

2 On the role of interactions among individuals and institutions in Schumpeter's analysis, see De Vecchi (1993).

3 In his view of invention as a social process, Usher drew inspiration from Gestalt psychology, which - originally developed in Germany – became popular in the USA in the 1940s.

4 Rosenberg (1963) cites the example of the profiling drill used in making the hub of bicycle wheels: here, the different speeds with which the inner and the outer part of the hub were worked led to excessive wearing out of the tool, and prompted research into the use of special steels.

5 New and older may lead to confusion. I am here referring to the introduction of a technology that is new with respect to the existing ones in a particular part of the system. Such a technology may indeed have been in existence before, in another part of the system or in a completely different system.