International Journal of Innovation Management
Vol. 11, No. 1 (March 2007) pp. 65–91

WHERE DO GAMES OF INNOVATION COME FROM? EXPLAINING THE PERSISTENCE OF DYNAMIC INNOVATION PATTERNS

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Received May 2006
Reviewed September 2006
Accepted October 2006

This paper contributes to explaining how and why distinct games of innovation emerge by suggesting that games are nested in innovation systems with persistent innovation dynamics. Dominant lifecycle models focus on how innovation systems transit from an effervescent stage, to product innovation, to process innovation, and so on. They propose specific mechanisms and limiting conditions that affect knowledge production and investment to explain these systematic transitions. Building on these models, we rethink the conditions and mechanisms of innovation to suggest that endogenous renewal cycles can re-create the knowledge and funding necessary to maintain innovation systems for long periods in one stage. We take steps towards developing a theoretical model of innovation dynamics that extends the applicability of lifecycle theories and unifies them with emerging views such as high-velocity innovation and hyper-competition. We also describe three possible types of endogenous renewal cycles, each sustaining a different level of knowledge dynamism and enabling different types of games of innovation.

Keywords: Innovation dynamics; innovation systems; knowledge production; innovation funding.

Introduction

Games of innovation can emerge only in the presence of persistent dynamic patterns of innovation (see Miller and Floricel, "Games of innovation", in this issue). This paper attempts to explain why dynamic patterns of innovation persist for long periods by suggesting that innovation systems continually re-create the knowledge and funding necessary to sustain the same forms and intensities of innovation. The prevailing model for innovation dynamics, the lifecycle model, overlooks persistence to focus on how innovation systems transit from an era of ferment, to product innovation, to process innovation, and finally to limited or no innovation. Lifecycle models contribute to our understanding of how technology and innovation evolve by explaining that innovation is not idiosyncratic, but evolves systematically through definable stages; that innovation occurs in systems, in which particular mechanisms determine transitions from one stage to the next; and that prevailing conditions limit innovation possibilities and paths. A large body of criticism refers to particular aspects of lifecycle theories, but no integral alternative has been proposed to replace them. Among others, critics argue that lifecycle models embed implicit assumptions about knowledge production and funds renewal that are unrealistic for most contemporary industries. In light of these assumptions, innovation processes appear very responsive to inherent limits in market and technology. These processes, in turn, lead to a lifecycle pattern.

We explore ways to extend the lifecycle theories to incorporate more recent ideas about competitive dynamics (e.g., high-velocity and hyper-competitive innovation) and ecological dynamics (e.g., resource systems and networks). We hope to make three contributions. First, lifecycle models capture well the dynamics of innovation at least through the first half of the 20th century and reveal systemic processes between customer needs, market evolution, product and process innovation, and the emergence of production systems and complementary assets. Hence, we analyse the assumptions of lifecycle theories in order to suggest ways for leveraging their useful aspects and replacing untenable assumptions with new ideas. This paves the way for explaining the dynamics now predicted by diverse theories with the same set of assumptions. Second, we combine insights from theories about meso-level innovation systems (Carlsson *et al.*, 2002; De Bandt, 1989) and social-systems persistence (DiMaggio and Powell, 1983; Giddens, 1984) to suggest ways in which institutionalisation processes can lead to systems that continually reproduce the same innovation dynamics. We argue that such systems are able to sustain endogenous renewal processes for knowledge and funding, two key resources for innovation. Hence, instead of shifting from one stage to another, innovation may persist for long periods in just one stage. Rather than treating them as inherent limits, we also reconceptualise the prevailing conditions for innovation as providing more or less potential for persistence in one of the stages. This basic argument is outlined in Fig. 1a and the theoretical model that we propose is presented in Fig. 1b.

The argument proceeds as follows. First, we outline the basic lifecycle model and identify explicitly its knowledge-production and value-creation assumptions. Then, we summarise the particular problems that others have found regarding these assumptions. We then outline a model of the processes and conditions that can enable

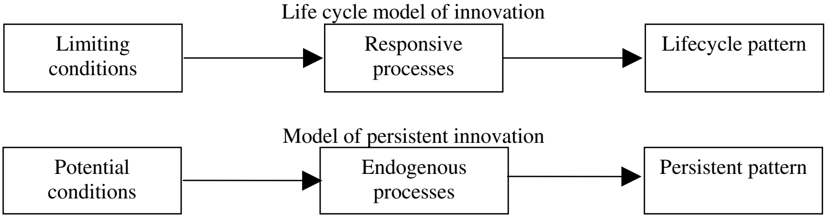


Fig. 1a. Determinants of persistent innovation dynamics: comparison of lifecycle and endogenous theories.

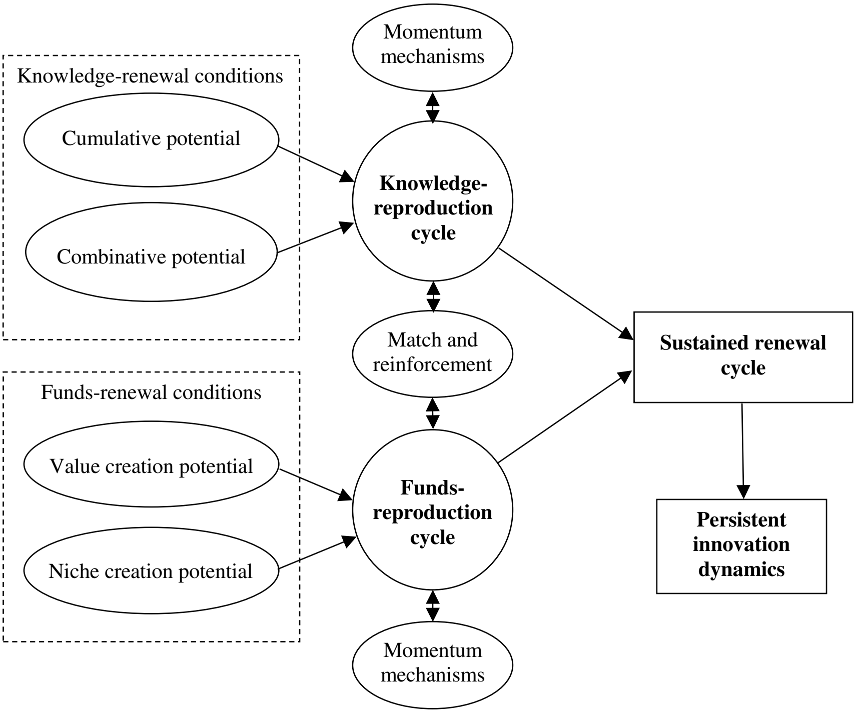


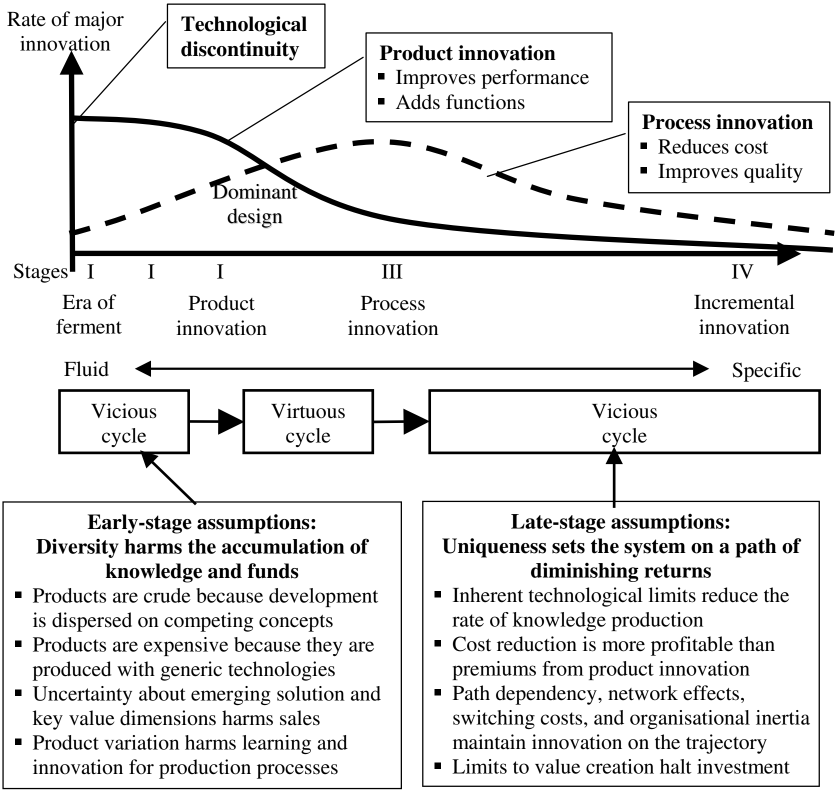
Fig. 1b. Determinants of persistent innovation dynamics: detailed determinants and influences.

the reproduction of knowledge and funding. Following this, we present three possible types of endogenous renewal processes that enable the persistence of innovation in just one stage. Next, we illustrate these processes with examples from biotechnology, digital electronics, and electrical industries. Finally, in our conclusion, we discuss theoretical and practical implications.

Theoretical Background

Innovation is a stream of action involving a series of activities that create and diffuse new useful products. It is motivated by opportunities for value creation resulting from novel technologies, new needs, fresh links between existing technologies and needs, or tensions and gaps between various components of current systems (Dahmén, 1970; Hughes, 1983; Pavitt, 1984; Schumpeter, 1950). Moreover, sustaining the stream of innovative action depends on continuing availability of different resources (Pfeffer and Salancik, 1978). Two resources, knowledge and funds, play a key role in reproducing the conditions for innovation, which include opportunity creation. Knowledge is an ingredient in any innovation opportunity because it creates a basis from which new horizons can be envisioned (Hargadon and Fanelli, 2002). Knowledge is also a vital resource for innovation activities, both directly, as a guide for technology and product development (Bohn, 1994; Fleming and Sorenson, 2004), and indirectly, as a basis for new product legitimacy (Van de Ven and Garud, 1993). Because any innovative activity produces new knowledge, knowledge is a good medium for feedback mechanisms. In turn, flows of funds seek innovation opportunities; their intensity correlates with the potential to create value. These funds can be used to finance the acquisition or development of most other resources, such as skilled personnel, equipment, and even knowledge. While some resources are more difficult to obtain, we consider availability of funds to be a good proxy for the availability of all required inputs.

Lifecycle models (Abernathy and Utterback, 1978; Klepper, 1997) explain how resources vital for innovation are created in four different stages through which innovation systems move sequentially (see Fig. 2). Systems transition from one stage to the next when they encounter inherent limits in the amounts of knowledge and funds that they can produce. The first stage focuses on the creation and early development of new technological knowledge, and is called “the era of ferment” (Anderson and Tushman, 1990). Many innovators enter the market with innovative products based on different operating principles and architectures. But products are crude and inefficient because knowledge-production efforts are dispersed around these operating principles and each major novelty disrupts the accumulation of know-how. Products are expensive because they are made with generic equipment. Value is also reduced by customers’ uncertainty about what concept will emerge



Early-stage assumptions:
Diversity harms the accumulation of knowledge and funds

- Products are crude because development is dispersed on competing concepts
- Products are expensive because they are produced with generic technologies
- Uncertainty about emerging solution and key value dimensions harms sales
- Product variation harms learning and innovation for production processes

Late-stage assumptions:
Uniqueness sets the system on a path of diminishing returns

- Inherent technological limits reduce the rate of knowledge production
- Cost reduction is more profitable than premiums from product innovation
- Path dependency, network effects, switching costs, and organisational inertia maintain innovation on the trajectory
- Limits to value creation halt investment

Fig. 2. The life cycle model and its assumptions (adapted from Abernathy and Utterback, 1978).

and by their confusion about what value dimensions they should use to compare products. This vicious cycle between knowledge and markets keeps investments and purchases low, so the flow of funds stays low. Innovation in this first stage is tenuous and short lived.

The era of ferment either dissipates on its own or evolves quickly into the next stage, in which a virtuous cycle between knowledge production and value creation enables significant product innovation. This stage begins when the market selects a single operating principle as “superior”. Because most innovation activities concentrate on the same technology, knowledge starts accumulating rapidly. Eventually, the technology converges on a typical architecture called “dominant design”, enabling further accumulation of know-how, which is no longer disrupted by frequent changes in product form. In the process, functionality is developed, and performance and reliability are improved. Costs also begin to decrease, as firms can now select process technologies that are more specific to a given form. The stabilisation of designs and the clarification of performance criteria also increase the value of products for customers (Clark, 1985). All of these lead to a rapid increase in sales. The confidence and the flows of funds from investors also increase. These inflows benefit fewer firms, as many firms with alternative designs are eliminated from the market (Suárez and Utterback, 1995). The remaining firms can invest even more in R&D and specialised production capacities. Investment in infrastructure and the development of complementary products also take off.

However, the product-innovation stage is replaced by a process-innovation stage. Knowledge production around a specific product form is bounded by inherent technological limits (Sahal, 1981). Firms, now competing directly for market share, shift their investments away from product innovation and towards process innovation and more specialised production capacities, which enable them to reduce costs. This enables further market growth, as new categories of customers join the market attracted by lower prices. Klepper (1996) explains the same shift in investment without assuming technological limits. He argues that product innovation, which adds functions and increases performance, comes from entrants and is appealing to new customers who are ready to pay a premium. On the other hand, process innovation, leading to cost reduction, usually comes from incumbents, who share a common knowledge base, and serves existing customers who are unable to pay a premium. But, as markets grow, any investment in process innovation produces a higher return for large firms than investment in product would produce for entrants by attracting new customers. Hence entry is reduced, and with it the production of new know-how.

However, the process-innovation stage also ends, this time because of limits inherent in process technologies, which erode the perspectives for new knowledge production from process-innovation efforts. And as markets approach the upper limit of product penetration (Bass, 1969), the potential for value creation from additional cost reductions is also limited. Firms shift almost entirely away from innovation towards increasing organisational efficiencies, including, in some cases, shutting down R&D facilities. Hence, inherent constraints activate a vicious cycle between knowledge production and value creation. These processes, fortified by path dependency (Dosi, 1982), switching costs (Shapiro and Varian, 1999), network effects (Arthur, 1989), and organisational inertia (Henderson and Clark, 1990), make this minimal innovation stage the only one that remains stable in the long term. New eras of ferment may arise around alternate operational principles, but these radical innovations come only from new entrants and often destroy incumbents altogether (Tushman and Anderson, 1986).

Criticisms of Lifecycle Theory Assumptions

Researchers question the automatic transition from one stage to the next by providing counter-examples of innovation systems that persist in just one stage. One example is biotechnology, which, after 30 years, is still in an era of ferment (Robbins-Roth, 2000). For over 40 years, the performance of semiconductors doubled every 20 months and architectures integrated a growing number of functions, as predicted by Moore's law (Moore, 1965; *Reuters*, 2003). In computers and electronics, a rapid sequence of dominant designs enabled decades of product innovation, with the constant addition of new functions and applications as well as exponential performance growth (Eisenhardt, 1989). Empirical tests show that the evolution of the electronics and computer industries does not follow the pattern predicted by lifecycle theories (Suárez and Utterback, 1995; Tushman and Anderson, 1986). Even for mature industries, McGahan and Silverman (2001) found no evidence of diminishing rates of product innovation or shifts to process innovation. The automotive industry, the empirical basis of the lifecycle model, saw constant product and process innovation since 1960 (Klepper, 1997), grafting new technologies onto a single dominant design and enabling continued enhancement of performance and functionality, as well as quality and cost. The petrochemical industry continuously innovates in production technologies (Klepper, 1997). The US electrical industry witnessed almost 70 years of exponential increase in scale and thermal efficiency in generation, leading to continuous price reductions (Hirsh, 1989). Our aim is to explain these persistent patterns of innovation building on some of the rich insights of lifecycle theories.

The mechanisms that drive the lifecycle concern the lack of accumulation of knowledge and funding, in light of certain limiting conditions considered to be given. In fact, research suggests that many systems reproduce knowledge and value-creation opportunities, based on endogenous feedback processes. In this way, the systems are able to overcome the apparent limits that impact innovation processes. For instance, one possible cause of the shift from product to process and to incremental innovation stems from inherent limitations in the dominant product technology. One way to overcome these limits is through research that produces a deeper mastery of natural processes (Bohn, 1994; Garud, 1997). Such knowledge-production processes enabled continuous innovation in domains such as semiconductors (Moore, 1965), biotechnology (Robbins-Roth, 2000), and chemical industry, in which core product technologies leverage specific processes. Moreover, for products in which several technologies are combined into highly interdependent systems, such as optical lithography equipment and hard disk drives, repeated research breakthroughs in processes that underlie component technologies were integrated through frequent architectural restructuring into the overall system, producing decades of constant performance increases (Chesbrough and Kusunoki, 2001; Henderson, 1995).

In more complex products, which are composed of a nested hierarchy of technical subsystems, the invention of new operating principles for subsystems, rather than a deeper understanding of natural processes, can overcome the limitations that these subsystems pose for the performance of the entire system (Hughes, 1983). For example, the invention of retractable landing gear enabled airplanes to overcome the speed limitations posed by fixed landing gear (Tushman and Murmann, 1998). To benefit from these advances, even complex products such as airplanes, for which high interdependence favours a stable integrated architecture (Murmann and Frenken, 2006), go through a long series of dominant architectures before the design stabilises. For other complex systems, a modular architecture, composed of separable subsystems (modules) whose interactions with other subsystems are rather limited and occur through well-defined interfaces, may be adopted. Modularity can be achieved if a certain loss in the efficiency of modules and in overall system performance is acceptable and if systems do not face severe constraints and poorly understood interactions (Chesbrough, 2003a; Ulrich, 1995). The study of innovation in microcomputers shows that, because knowledge can develop independently for each module and system-level learning can easily benefit from trying many different architectural combinations, innovation in modular products is less constrained than innovation in integrated products (Langlois, 1992).

A second way of continuing to produce knowledge beyond the apparent technological limits is through diversity. When technologies and their underlying knowledge bases are heterogeneous, different parts can be combined and recombined in very different ways. A higher number of possible combinations increase the chances that a superior solution will be found (Cohen and Malerba, 2001). Diversity also simulates creativity (Hargadon and Sutton, 1997). For instance, the telecom industry now benefits from a larger number of underlying technologies, including transmission media such as wireless, fibre-optics, simple cable, coaxial cable, microwave, and so on; transmission principles such as broadcast, line switch, and packet switch, each with many different protocols; and specifics of compression for different signals, such as voice, video, and data. Crosspollination and architectural permutation within this diversity freed the development of telecom systems from the limitations of the traditional knowledge base, enabling relentless innovation in functionality, as well as performance increases and cost reductions. To facilitate the endogenous emergence of new combinations, the development of architectural standards for telecommunications focuses on simplifying the interoperability between different technologies and subsystems, while also increasing the separation between different layers of the architecture to achieve a higher degree of modularity. Hence, conditions that enable continuing technological discovery, learning, or recombination can explain innovation patterns that contradict the lifecycle models.

Another force driving innovation systems along a lifecycle is the reduced scale of innovative activities that precludes knowledge accumulation even if there is enough exploration potential. Many authors have observed that knowledge accumulates in distributed networks rather than in firms. For instance, in the biotechnology sector knowledge accumulates in interpersonal networks that span the academic and industrial worlds (Powell *et al.*, 1996). In the computer, software, and telecom industries, knowledge accumulates in inter-firm networks built on the basis of alliances to promote an architecture proposed by a leader firm (Iansiti and Levien, 2004), or of regional agglomerations such as Silicon Valley, or of standardisation bodies. This "open innovation" approach enables the pursuit of initiatives that would be rejected by a single firm (Chesbrough, 2003b). In more stable industries, such as Finnish pulp and paper, Danish wind turbines, and Japanese automobiles, inter-organisational networks with strong ties enable distributed learning that benefits all participants (Clark and Fujimoto, 1991; Garud and Karnøe, 2003). In other industries, some actors specialise in the accumulation and development of knowledge. For instance, in the petrochemical industry, specialised equipment and engineering firms accumulate knowledge from research and from the different projects in which they participate and transform it into specific solutions for subsequent clients (Klepper, 1997).

Process innovation can also, to a certain extent, be decoupled from product innovation and from the existence of a dominant design. Flexible manufacturing technologies and processes, flexible networks of partners, and outsourcing reduce the cost of changing production technologies as a result of changes in design (Clark and Fujimoto, 1991). By participating in many different projects, equipment manufacturers and network partners continually develop and accumulate specialised process knowledge, which enables them to continually innovate in their area of expertise. In sum, a particular innovation system structure enables continuous knowledge production that may correspond to any of the stages of the lifecycle model.

Another set of forces of the lifecycle model is the value-creation limits that diminish the inflows of funds for innovation. But in some cases, social needs and interests, as for biotechnology in light of the ageing population or for weapons during prolonged conflict periods, along with a munificent environment in developed nations, create lasting opportunities for value creation so that markets emerge, people buy, investments are made, and governments step in, leading to a continuing era of ferment. In other cases, perhaps as a result of competitive threats, entire industries realise that their collective survival depends on innovation. Hence, firms adopt a hyper-competitive stance, aggressively investing in product innovation rather than focusing just on process innovation or organisational efficiency (d'Aveni, 1994; Thomas, 1996).

Customer needs are also heterogeneous, opening different avenues and niches for value creation (Day, 1990). In the personal computer and VCR industries, a particular configuration of user needs and demand led, contrary to the typical lifecycle sequence, to significant process innovation before any major product innovation, in order to reduce prices and enable market growth. Only when prices reached a floor below which customers become less sensitive to any further reduction did significant performance increases and additions of new functions and features occur (Adner and Levinthal, 2001). While desktop computer producers were mostly interested in having higher memory capacities in hard disks, laptop producers also wanted smaller dimensions and low energy consumption (Christensen, 1997). This created a niche for new entrants that pursued innovation strategies that renewed the industry, while most incumbents' behaviour was typical for later lifecycle stages. The assumption that new entrants can attack high-performance and premium-priced niches only because the mass market is occupied by incumbents that reap economies of scale (Klepper, 1996; Suárez and Utterback, 1995) is also contradicted by numerous examples of successful entrants that started in low-performance niches and targeted users that could not afford existing products (Christensen and Raynor, 2004; Day, 1990). Moreover, the diversity of needs enables firms to have heterogeneous capabilities. The insulating mechanisms (Barney, 1991; McGee and Thomas, 1986) that protect these capabilities from imitation or acquisition by competitors contribute to creating value-capture niches that attract resource flows for innovation.

In sum, the assumptions of lifecycle theories can be grouped in two themes. In the early stages, diversity stifles both knowledge and value creation, and it activates a vicious cycle between them. In later stages, uniqueness sets systems on a path of intrinsically diminishing returns for both knowledge-production and value-creation processes, reactivating a vicious cycle between them that limits investment in innovation (see Fig. 2). However, critics point out that diversity is a key enabler of knowledge production through recombination or crosspollination between separate knowledge areas (Cohen and Levinthal, 1990; Katila, 2002; Rosenkopf and Nerkar, 2001). It also opens possibilities for value creation by creating market and capability niches, which improve the value-capture opportunities and hence create favourable investment conditions (Day, 1990; Wernerfelt, 1984). Moreover, critics suggest that cumulative knowledge production, even in a single area, is practically unlimited; the onset of diminishing returns can be delayed by building on existing knowledge to test, refine, and validate it, or to create new knowledge (Bohn, 1994). In turn, investment in innovation can continue unabated when needs are stringent and previous value creation provides a munificent environment for investment in innovation (Von Hippel, 1986).

Model of Innovation Persistence

The criticisms discussed in the above section suggest that innovation can continue for long periods if prevailing conditions provide the potential for continuing knowledge production and renewal of funds for innovation, and if innovation systems develop processes that can sustain the continuing reproduction of knowledge and funds. These insights are grouped in the theoretical model presented in Fig. 1b. Based on the above discussion, we argue that the knowledge-production potential depends, on the one hand, on the available "space" for cumulative development. This space is related to the complexity of the natural phenomena underlying the functioning of technical artefacts, which offers the potential for lasting cumulative advances in the scientific knowledge applicable for innovation (Feynman, 1959; Kutschera and Niklas, 2004; Mayr, 2000), and to the complexity of technical systems, that is, the number of constitutive elements and interactions between them (Hobday, 1998; Miller *et al.*, 1995; Ulrich, 1995), which offers the potential for modular innovation, architectural reconfiguration, and lasting experiential learning about these artefacts. On the other hand, continuous knowledge production depends on recombination potential, related both to the diversity of relevant knowledge and to the ease with which knowledge can be transferred from one technical domain to another and from one application to another (Katila, 2002; Szulanski, 1996).

The funds-renewal potential depends, on the one hand, on the salience of needs and the munificence of the environment, which enable continuing investment. On the other hand, it depends on the ability to create value-capture niches, related to the diversity of needs and circumstances (Hayek, 1945), and to the presence of structuring mechanisms, such as institutional frameworks (Stigler, 1971; Van de Ven and Garud, 1993), economies of scale and scope in innovation and operations, network, and reputation effects (McGee and Thomas, 1986; Scherer, 1990; Teece, 1986), which create asymmetries between participants.

More importantly, literature also suggests that momentum mechanisms prompt innovation systems to persist in a pattern of innovation. Specific patterns of knowledge accumulation and exchange among participants produce a "momentum that enables and constrains the activities of distributed actors" (Garud and Karnøe, 2003, p. 277) and reproduce the patterns. Continuous innovation and hyper-competition enter shared cognitive frameworks and organisational practices, which, in turn, help to reproduce the pattern (Bogner and Barr, 2000; Brown and Eisenhardt, 1997; Floricel and Miller, 2003; Jelinek and Schoonhoven, 1990). Customers get used to a rhythm of innovation and to regularly paying premiums for new products to ensure interoperability with peers and complementary products (Adner and Levinthal, 2001), producing steady inflows of funds that can be reinvested in innovation.

In addition to favourable conditions and momentum mechanisms, persistence relies on endogenous processes that reproduce knowledge and funds. In such processes, one outcome of innovation is conditions that generate more innovation of the same kind, creating a virtuous renewal cycle. Lifecycle theories suppose that such feedbacks occur, but only for a limited time, particularly in the product-innovation stage. On the other hand, innovation systems theories suppose that positive feedbacks at different aggregation levels support persistent innovation dynamics

(Carlsson *et al.*, 2002; Freeman, 1988; Malerba, 2002; Porter, 1990; Powell *et al.*, 1996).

We argue that endogenous resource reproduction processes rely on specific innovation system configurations. Systems are broad enough to encompass a technological cluster (Carlsson *et al.*, 2002) that supports the knowledge-reproduction cycle, as well as institutions and value nets that support a complete endogenous funds-renewal cycle. Despite their fluid boundaries, such systems emerge as coherent self-perpetuating relational nexuses (Anderson, 1999). Such a system is, to use one of Schumpeter's, famous phrases (1950, p. 82), "by nature a form or method of economic change that not only never is but never can be stationary". Key insights about its nature can be derived from the literature on dynamic innovation systems. Systems with persistent innovation dynamics alter their structure in order to facilitate the entry of new firms and to more easily redistribute funds towards innovative ideas (Thomas, 1996). They develop network structures that facilitate the broad search and crosspollination of knowledge and ideas (Powell *et al.*, 1996). Researchers referring to the competitive stance of incumbent firms suggest that rather than resisting and ending up being destroyed by new ideas, these firms not only build upon, but even help legitimise and generate innovation by new entrants (Iansiti and Levien, 2004; Podolny *et al.*, 1996). Three possible forms of endogenous resource reproduction based on knowledge feedback are discussed below.

Three Types of Endogenous Resource-Renewal Processes

Understanding how endogenous resource renewal takes place concretely calls for analysis of the different aspects of the innovation process. Activities that are, broadly speaking, relevant for innovation are customarily classified into four categories, sometimes seen as sequential stages in the flow of innovation activities: scientific, technology development, product development, and operational. Each of these activities requires different types of resources, such as knowledge, funding, skills, and equipment, and each produces different types of knowledge and other valuable outputs. Scientific activities aim to produce knowledge that explains natural phenomena, including those occurring in technical artefacts and production processes. Because this knowledge may not have an immediate practical relevance, scientific activities can seldom count on commercial funding sources. Such activities require highly skilled personnel and take place mostly in universities and public labs that are subject to institutionalised criteria for determining the "truth".

By contrast, the other categories aim at practical uses. They take place mostly in industrial firms and associations, and stress the effectiveness and efficiency of action. They are funded predominantly by commercial sources, although each category calls for a different level of risk tolerance. Technology development includes the discovery and demonstration of operating principles and of basic technical concepts and architectures, and the growth of a common base of analytical tools and methods that can be used for products and services. Product development includes characterising customer needs and market dynamics, and translating this understanding into technical specifications and marketing strategies, as well as developing and testing concrete, functioning products and production processes. Finally, operational activities refer to production and commercialisation activities that make and deliver products and services to the final users and assist them in using, maintaining, and repairing these goods.

The key difference between our argument and that of lifecycle theories is with respect to the emphasis we place on the interactions between these types of activities. Simply put, lifecycle theories emphasise processes in which the outputs of one type of activities enable and trigger other types, typically downstream. For example, the results of technology development enable the development of new products, which, in turn, enables production and commercialisation. Our theory emphasises processes in which the outcome of an activity naturally creates a stimulus and provides resources that enable the pursuit of "upstream" activities or activities in the same category, creating the potential for feedback cycles that lead to persistent innovation.

By studying the different empirical patterns of continuous innovation discussed above, and by analysing the nature of knowledge production and of the resource flows between activities, we came to the conclusion that three types of configurations are likely to lead to sustainable resource-renewal cycles. Each of these cycles is dominated by a pair of activities that are close to each other in the "sequential" list of four types presented above. This closeness is not accidental; it reflects a certain resemblance in nature between the resources and activities appearing within each pair. For example, despite their different goals and criteria, science and technology development involves an element of discovery and relies on highly skilled personnel. For certain classes of products, such as drugs and semiconductors, a better understanding of natural processes, the typical aim of science, is also the key condition for the development of core product technologies. Because of this closeness, these pairs of activities are more easily made commensurate and eventually synchronised in an innovation system.

The *science-based cycle* relies on the co-evolution of scientific and technology development activities (Murray, 2002). It emerges around knowledge transfers from science that suggest new technological principles and enable rapid growth in the knowledge base and feedback from technology development to science in the form of new research questions or new data. The cycle persists between scientific domains in which long periods of rapid cumulative advancement take place and a rich cluster of applications appears, which ensures that technology development feeds back a wealth of knowledge and questions to science. Innovation is effervescent and involves the parallel development of many applications based on distinct principles. Because of the advanced and not entirely explicit nature of the transferred knowledge, the carriers of knowledge flows that span the scientific and technological realms are usually individuals originating in universities that establish small entrepreneurial firms or are hired by large firms. Due to the risks involved, small firms depend on the ability to attract government support and venture capital, including "strategic" venture-capital investment by large corporations. Based on expectations about market emergence, these fund providers often receive a direct or indirect return on investment before innovations reach customers. This uncouples the funding for scientific and technology development from actual commercialisation revenues, enabling the cycle to persist for long periods of time. The typical example is the biotechnology sector, but nanotechnology, new materials, and new energy sources are other sectors in which such cycles can potentially emerge.

The *technology-based cycle* combines technology and product development activities. Technology development enables the development of prototypes and products. In turn, product development raises new technical problems that stimulate technology development and provides new ideas, possibilities, and modules that can be combined into new technologies. While totally new operating principles enter the cycle from time to time, including some based on scientific advances, innovation comes mainly from the recombination of existing knowledge, and results in frequent waves of architectural restructuring around stable principles (Henderson, 1995). Hence, the persistence of this cycle depends on the existence of a critical mass of diverse, yet related, technologies. Knowledge recombination is paralleled by a rapid redistribution of funds to emerging opportunities, which combines venture capital investment that lowers the barriers to entry for innovative start-ups, and intra-company reinvestment of revenues into "next generation" research, venturing, and product development. Examples include sectors such as computers, software, telecommunications, Internet, multimedia, and MIS, as well as the sectors resulting from their convergence.

The *experience-based cycle* combines product-development activities and operations. Product-development activities result in the availability of new parts, equipment, and tools that can be produced and commercialised. In turn, the experience gained in the long-term production and marketing of these products suggests new needs or new product ideas, improvement opportunities for existing products, and production processes; it also provides cheaper and better materials, tools, and equipment. Innovation consists of incremental improvements in existing products and processes and of new products that rely on the existing knowledge base and operational capacities. Innovation is enhanced by information technologies that capture the knowledge base and expand the coordination and control capacities in production. Science can increase the mastery over products and processes and solve detail-level problems but does not lead to spectacular innovation. The funding for innovation in this cycle relies heavily on corporate reinvestment in new product development. Because funds come almost exclusively from revenues obtained in exchange for the value that firms create for customers, the persistence of this cycle depends on firms' ability to retain the value they create and redirect part of it for innovation. Examples include the automotive industry after 1960, and the power industry (1900–1970).

Table 1 compares the three types of endogenous renewal processes in terms of the theoretical model presented in Fig. 1b. The existence of these possible pathways for resource renewal enables the coalescence of innovation systems that both rely on one of these processes and reproduce them through the social and cognitive momentum mechanisms described above. Instead of gradually sliding into the next stage of activities, such systems will seek to justify the same type of goals, and attract the same type of resources, in order to replicate the same type of innovation activities. The result is persistent dynamics of innovation.

Three examples

Below we illustrate these three types of systems with examples from the biotech sector, digital industries, and the US power industry (1900–1970). The examples should not be read as empirical evidence for the theory presented in this paper but as a demonstration of this theory by means of descriptions that show how the general mechanisms advanced in this paper play out in concrete system configurations. The cases build on secondary data, academic publications, and our own empirical studies.

Biotech innovation system: vibrant science-technology co-evolution

The system emerged in the early 1970s and has sustained effervescent innovation since then, fuelled by a revolution in the understanding of biological processes, which greatly increased the number of therapeutic targets and suggested new ideas for disease prevention and cure (Robbins-Roth, 2000). Knowledge renewal is driven by rapid cumulative advances in two core scientific disciplines: molecular biology and biochemistry (McMillan *et al.*, 2000). The potential for further knowledge production is very important because the phenomena that biotech firms study are inherently complex, defying reductionism and calling for explanations that integrate several levels of reality (Mayr, 2000). Moreover, while the objects of physics (electrons, atoms) are "uniform and invariant in their characteristic traits and behavior, the

Table 1. Comparison of the three types of cycles in terms of the conditions enabling innovation persistence.

	Science-based	Technology-based	Experience-based
Innovation dynamics	Constant flow of new technological principles based on new scientific paradigms and discoveries	Many new applications and functions; exponential growth of performance in core technologies	Steady cost reduction; higher penetration and reliability; new applications of standard capabilities
Potential for			
Cumulative discovery	High	Average	Average
Combination	Average	High	Average
Knowledge-reproduction cycle	Feedback between scientific and technology development activities	Feedback between technology- and product-development activities	Feedback between product-development and operational activities
Knowledge momentum	Rapid sequence of scientific waves	Dominant pace of technology renewal and performance increase	Expectations of constant increase in scale and scope of operation
Potential for			
Value creation	High	High	High
Niche creation	High	Average	Average
Funds reproduction cycle	Venture capital reinvestment and renewal of government funds	Hyper-competitive reinvestment by industrial firms and venture capital	"Build and grow" reinvestment by firms enjoying monopolistic positions
Funds momentum	Creating scientific ethos, defence of IP barriers and growing legitimacy	New technology organising visions and faddish cascades for products	Defence of regulatory barriers Ethos of modernity and novelty

IP: Intellectual property.

organisms biologists study manifest astonishing variation" (Kutschera and Niklas, 2004, p. 255). Individuals are the main carriers of science flows; scientists "jump to industry" or encourage collaborators to do so (Zucker *et al.*, 1998). Many biotech firms locate close to major universities, and some of the scientists whom they employ never totally leave academe.

Ideas coming from science go through a long technology development and legitimation process, during which firms make new observations and raise questions that are fed back to science. Some firms encourage researchers to publish these results in order to maintain a scientific reputation, which eases the access to funds (DeCarolis and Deeds, 1999). Individuals who return to universities after failed attempts also bring back new knowledge produced in the technological realm. The direct combinative potential of knowledge resulting from technology development seems low (Murray, 2002), perhaps because of its advanced and specific nature. Instead, the scientific community synthesises technological and scientific advances into new paradigms and theories. Firms also produce methods, databases, and tools that open new opportunities in scientific and technological research. For instance, the mapping of human genome was first realised by a firm that wanted to commercialise this information (Davies, 2001).

While innovations rely on common paradigms and platforms, the narrow application areas create many differentiated niches. Within these niches, ideas are protected by intellectual property laws and, as development advances, by catch-up costs and regulatory barriers. Funds renewal relies heavily on investments from governments, mainly in academic research, venture-capital, and large pharmaceutical firms. The success of some companies that were founded in the 1970s triggered large venture-capital inflows that lowered entry barriers for start-ups. Many one-project firms propose innovations based on distinct operating principles and compete against each other in a race towards commercialisation. Most firms soon disappear, but others obtain new rounds of financing from sources with lower risk tolerance. Because rewards are huge, it takes only a few winners to reproduce the whole venture-funds renewal cycle. Successful start-ups often "relay" (Olleros and MacDonald, 1988) their knowledge and rights to other firms, usually large pharmaceutical companies, because they lack the required product-testing skills and marketing capabilities to achieve commercialisation. Both firms and venture capitalists reap benefits well before the product reaches the market and can focus on upstream activities. In turn, large companies can avoid investing early in a myriad of uncertain technologies and can specialise in funding and performing downstream activities. To reduce risk, both large and small firms contract out some innovation activities. This creates niches for firms providing R&D tools, information databases, upstream support services, such as compound or tissue characterisation, or downstream services, such as clinical trials. Hence, the renewal cycle in the biotech sector combines three "games of innovation" (Miller and Floricel, Games of Innovation, this issue): science-to-technology races, research tools and services, and safe science-based products.

The system has a high value-creation potential due to the growing attention to health by an ageing but wealthy population. A superstructure dominated by scientists, and including advocacy groups, government agencies, "science" reporters and authors, and other entities, plays a crucial role in the societal reallocation of funds to biological research by promoting fundamental advances as a source of major benefits in health care as well as agriculture and industrial processes. It also creates faddish waves around new paradigms, such as genomics and proteomics, in order to attract inflows of venture capital. Moreover, it advocates the need for longer patent protection, which enables the reproduction of funds.

Digital innovation system: forward-looking technology recombination

This system has a technological core, composed of semiconductors, computers, software, and, lately, telecom equipment, and two different application areas: on the one hand, consumer products, such as multimedia, telecom services, and Internet; on the other, information and communications systems for corporate clients. For the last 40 years, this system has produced exponential increases in performance, miniaturisation, and integration in the core technologies, paced by Moore's law (*Reuters*, 2003). It also added new applications and increased the performance and functionality of existing ones. Most technologies and products build on the same basic principles. Academic research provides important inputs, such as the input of quantum physics in semiconductor technologies (Feynman, 1959). But the key sources of knowledge and innovation opportunities are the latest technologies and products developed by sector participants and new entrants, which are recombined into new technologies, products and systems. For example, the development of the Internet, with its protocol (IP) and infrastructure, enabled the development of the IP telephony, whereby voice can be transmitted over the Internet. As this technology emerged, firms targeting consumers started proposing services such as conferencing and video transmissions, while those focusing on corporate clients used them to inject new capabilities into clients' processes. Advances in core technologies enable new applications, which, in turn, impose new requirements on those core technologies, stimulating further capacity increases and functional additions.

The combinative potential is high because the attitude is one of "open innovation" (Chesbrough, 2003b), there are a large number of relevant technologies, and the digital nature of systems and the increasing capacity of core technologies enables modular separation (Schilling, 2000; Simon, 1981). Modules are recombined in new multilevel architectures, and architectural restructuring is a main source of innovation. Because modules are being developed by different firms, technological advances often rely on the anticipatory elaboration of architectural standards. For instance, the IP Multimedia Subsystem (IMS) standard proposes a three-layered architecture that enables communications and content access not only for voice but also for text, pictures, and video by reusing functional and infrastructural modules across applications (see, for instance, Ericsson, 2004). The main game of innovation in this system is "battles for architectures" (see Miller and Floricel, Games of Innovation, this issue), with "systems engineering and consulting" dominating the industrial customer-oriented applications.

New technologies and modules create specialised niches that may attract funding. Ideas are not as well protected, but funds renewal is faster than in biotech, because development is less costly and usually done inside one firm; products reach the market or fail much faster. Many important ideas come from entrants, and most participants understand that a stream of entrants fuels the dynamism of the entire system (Thomas, 1996). The availability of venture capital reduces the barriers to entry. Established firms also invest in start-ups or join a number of niches, helping legitimise them in the process (Podolny and Stuart, 1996). They support ecosystems of small firms by helping them develop complements or applications around their products (Iansiti and Levien, 2004). But the system is also fuelled by final customers paying for industrial and consumer applications. An incessant barrage of new or better products and applications, involving photos, music, video, or financial transactions, ensures a growing inflow of funds. A significant portion of these funds returns to core-technology suppliers, who can spread the increase in development costs, due to eventual diminishing returns, over a much larger number of applications.

A superstructure of associations, consultants, publications, and other entities develops and legitimises architectural standards, reducing uncertainty for both vendors and clients, and creates faddish waves in technology, such as JAVA, to stimulate flows of investment in technology development, as well as in applications, such as e-commerce, e-collaboration, and e-procurement, for corporate clients, and new "gizmos" for individual consumers, to stimulate purchases by clients. Beyond agglomerations such as Silicon Valley, the superstructure fosters virtual discussion groups and design communities that create weak links between players, helping the exploration and recombination of emerging technologies.

US electrical innovation and production system (1896–1970): Momentum of experience

The "grow and build" (Hirsh, 1989) innovation dynamic of this system was driven by economies created by using central stations to serve large areas. High-voltage transmission, enabled by innovation in transformers and the adoption of polyphase alternative current, reduced the loss of power between stations and users. To profit from this opportunity, in 1903, Samuel Insull, owner of a Chicago firm, challenged GE to supply a 5-MW steam turbine generator for one of his stations. This unit was much larger than reciprocating steam engine units common at the time (McDonald, 1962). The experience gained in making and operating this equipment served in the design of new, larger units, leading to persistent increases in scale. In 1908 the largest units generated 35 MW; in 1922, 175 MW (Energy Information Administration, 1996). Exponential capacity growth resumed after the Second World War, thanks to new materials, turbine shapes, and steam-generation techniques. Units reached 1300 MW in 1973. Similar experience-based knowledge cycles supported the construction of ever-larger networks and innovations in domestic appliances and industrial electrical equipment.

By tinkering with "junk piles" of obsolete ideas and machines and synthesising mountains of detailed observations and data into fundamental principles (McDonald, 1962, p. 106), Insull and others learned the fundamentals of the business. Central stations needed a large customer base, which triggered a wave of consolidations of small electric firms in the 1890s. Serving different demand patterns with one system led to major savings, so firms began to serve suburban and rural areas, urban transportation (tramway), and industrial loads. Demand was stimulated by aggressive price cuts and rates that decreased with consumption, as well as by innovation in appliances and electricity-powered equipment, many of which were made by firms such as GE and Westinghouse that were dominant in the generation-equipment business. Characters such as Reddy Kilowatt (1934) and campaigns such as "Living better electrically" (1956), which equated electricity with progress, promoted consumption. Hence, electricity prices fell throughout the period, leading to a manifold increase in penetration and consumption and to gradual replacement of old systems, such as gas lighting.

All of this made huge flows available for ex-post reinvestment. But when it came to attracting funds for initial consolidations and purchases of innovative equipment, the short-term municipal franchise system, prevalent in the late 1890s, provided insufficient protection. Insull (1898) was the first to propose a system of private monopolies supervised by state regulatory commissions. Other owners were sceptical initially, but later accepted his idea, pressed by a growing municipal ownership movement. Backed by industry-sponsored reports (see Commission on Public Ownership and Operation, 1907), and by Progressive governors, who doubted the ability of corrupt city councils to regulate the sector, New York and Wisconsin adopted the regulated monopoly system in 1907, soon followed by all other states. Under this system, franchises were virtually unlimited and a return on investment was guaranteed under uniform accounting rules. This eased financing in public markets. To further facilitate financing and to achieve an efficient scale for engineering and construction, regulated utilities in different states were consolidated into holding companies. By 1927, 16 holding companies controlled 75% of US electricity generation. The pyramidal structure and the collapse of some holding companies, including Insull's, were blamed for precipitating the depression, but recent studies show that the customers of holding companies paid less than did those of other suppliers (Emmons, 1993, p. 891). Franklin D. Roosevelt's 1935 reforms dismantled holding companies but maintained most of the regulated monopoly system and corrected some of its weaknesses.

Once installed, the "grow and build" dynamic acquired significant inertia and became part of the sector's culture, reinforced by an increasingly tight network structure. Hence, firms forecasted demand growth and prepared in advance for it by ordering larger equipment. But the reproduction of this dynamic was disrupted in the late 1960s. Hirsh (1989, pp. 100–109) argues that the "stasis" of the system was due not exclusively to inherent limits in power-plant technology, but especially to learning problems, as engineers extrapolated to larger-scale unit without sufficient feedback from operational experience. The strong demand of the 1960s increased the order backlogs and the delays in plant construction. It took 8 years before operating feedback could be obtained for new units. In the late 1960s, many large units built without appropriate learning experienced problems. Utilities and manufacturers soon backed away from them and ordered smaller units. Around 1970, electricity prices began to rise for the first time.

The "games of innovation" that are prominent in this innovation system are "asset-based optimisation" for utilities; "innovating in packs" for power-equipment suppliers, which often maintain long-standing alliances with large utilities; "learning and marketing" for electrical appliance manufacturers; "systems engineering and consulting" for engineering and construction firms; and "niche craft problem solving" for some specialised engineering consultants and equipment suppliers.

Conclusion

The model presented in this paper suggests that lifecycle theories have limited predictive power because their assumptions are too restrictive and they emphasise only certain mechanisms. Hence, they assume that innovation always has a limited potential and accept only a narrow range of endogenous mechanisms. As a result, they predict that systems cannot persist in stages with vibrant innovation and shift to incremental or no innovation stages. By proposing a broader range of conditions and mechanisms, our theoretical model suggests a way to extend the applicability of lifecycle theories and unify them with other, less theorised views, such as high-velocity innovation and hyper-competition. Our model contributes to the literature on innovation systems by proposing reasons and mechanisms that explain the existence, vitality, and dynamics of innovation systems.

The possibility of different types of persistent innovation dynamics also explains the difference between games of innovation that emerge in different knowledge-production contexts. The science-based resource-reproduction cycle corresponds to games with high knowledge-production dynamism; the technology-based reproduction cycle corresponds to games with average knowledge-production dynamism; and the experience-based reproduction cycle corresponds to games with low knowledge-production dynamism. The reproduction mechanisms that sustain these cycles and the persistence of the innovation dynamics create a situation in which the respective levels of dynamism are considered as given, leading to the adoption of strategic and organisational practices that are adapted for the respective knowledge-production and innovation contexts.

Our theory does not suggest that conditions for persistent innovation dynamics emerge naturally and that renewal mechanisms can sustain a type of innovation dynamics indefinitely. Innovation systems that appear to support such dynamics are a fact of the last half-century, and their emergence may be related to a more profound institutionalisation of innovation as a source of competitive advantage and social wealth, and to the emergence of institutions such as government research funding and venture capital. But understanding these conditions and mechanisms suggests ways for developing the new economy and extending its impact in such key areas as energy and housing. Moreover, this understanding can help explain why persistent innovation systems are able to exert such an important influence both on participant firms and on the society as a whole. Our model shows that, in certain conditions, innovation systems are able to carve out of the societal environment the conditions that enable their own survival and growth.

Acknowledgements

The research presented in this paper has been financed by the MINE programme. The authors wish to thank Xavier Olleros, Roger Miller, Raghu Garud, Mike Hobday, Danielle Dunne, Dorothy Kirkman, and several anonymous reviewers for their comments on earlier versions.

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