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REGULAR ARTICLE

Niches in evolutionary theories of technical change

A critical survey of the literature

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Abstract In this article, the use of the niche concept for explaining radical technical change is explored. Contributions of various strands of literatures are elaborated and systematized in a taxonomy. Radical change or technological discontinuity is defined as the establishment of a new sociotechnical regime. Sociotechnical regimes carry and store rules for how to produce, use and regulate specific technologies. They perform the task of genes and define the boundary between technological species. It is proposed that radical change is generated by four different evolutionary mechanisms and patterns: natural selection, punctuated equilibrium, market niche selection, and technological niche selection. In each pattern, a different type of niche is implicated in the change process. The difference between niches results from differentiating between two dimensions: (1) whether niches are internal or external to the prevailing sociotechnical regime; (2) whether rules for design and use of a specific technology are stable or unstable within the niche.

Keywords Niche · Evolutionary theory · Discontinuity · Technical regime

JEL Classification N00 · O31 · O33

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1 Introduction

It is surprising that little systematic attention has been given to the topic of niches in evolutionary theories of technological change. Recently, a number of scholars have sought to conceptualize the role of niches, but this has not often been treated as a central issue for further theory development. Following scholars such as Tisdell and Seidl (2004); Kauffman (1995, 283), and others, we argue that the challenge for future work is to build a theory as to the way in which technical change drives its own transformation by the persistent creation of new niches. Our aim is to provide building blocks for such a theory. The development of a niche theory is particularly important because it will shed light on the far from fully understood issue of the creation and survival of novelty leading to discontinuity and hence the establishment of new technological species.

This article starts with a historiographical overview. We will explore systematically how niches have been conceptualized in various evolutionary theories of technical change coming from different traditions: evolutionary economics (e.g. Levinthal 1998; Nelson and Winter 1982; Saviotti 1996; Ziman 2000; Malerba et al 2003), history of technology (e.g. Basalla 1988; Constant 1980; Mokyr 1990a), science and technology studies (e.g. Rip and Kemp 1998; Schot 1998) and technology management (e.g. Rosenkopf and Tushman 1994; Van de Ven and Garud 1994).[1] It is important to note that, although we discuss and use the existing literature, we do not always follow particular understandings put forward by introduced authors. Our main aim is to use their interpretations of evolutionary change to elaborate more systematically on the role of niches. This elaboration often builds on the important insight that niches must not be seen as resource spaces that pre-exist waiting to be filled in. Instead, we emphasize that they develop as a product of agency. Innovators do not succeed, in other words, because their innovations fortuitously fit into predefined sets of niche constraints; rather, they construct their own niches. We are not able to do full justice to the work of the 'shoulders we stand on' but rather select, discuss and sometimes reformulate those elements, which help to create a better understanding of the role of niches in technical change. A discussion that includes evolutionary accounts from a range of disciplines and literatures is rare. Yet it is precisely the combination of insights from the various traditions that sheds new light on the development of new technological species and hence on the origins of discontinuity.

In the second part of this article, we will show the complementarity of the various conceptualizations of the role of niches, and by doing so bring forward the varied kinds of niches that play a role in technical change. We will critically discuss and

[1] Social scientists and historians typically have to explain (and almost apologize) why they want to use a biological analogy. Following Ziman (2000) and Hodgson (2002), our starting point is that advancing an evolutionary theory is not so much an analogy with biology, as an application of a more general theory. Still, as we will show, for studying technical change, it is useful to look at biological evolution for inspiration and ideas because it has been studied in such depth. At the same time, we are aware of the vast differences between biological and technological evolution, and these are crucially important for understanding the role of niches as we will show in this article.

develop a taxonomy of four different basic evolutionary mechanism (and patterns of change that follow from them) responsible for discontinuity in technical change: natural selection, punctuated equilibrium, market niche selection and technological niche selection. For each pattern, we will highlight the specific role of niches.

2 Natural selection

The central tenet of a Darwinian evolutionary theory can be summarized as "blind variations selectively retained" (Campbell 1960, cited in Ziman 2000). This summary contains not only the three basic elements for an evolutionary theory of technical change (variation, selection and retention), but also a framework for how these three elements interact. We begin our exploration with a brief discussion of all three elements. Here we follow Basalla (1988), and Nelson and Winter (1977, 1982; see also Nelson 1995), albeit selectively. In particular, we highlight elements in their work and of others that help to elucidate the role of niches in natural selection processes.

Within a natural selection theory, technological variation is assumed to be ubiquitous and to a large extent random in direction. There are always a range of possible new designs available, coming out of R&D processes, user contexts and subsequent user–producer interactions. The *direction* of the evolutionary process is not determined by the process of variation generation, but by the selection process. This process preserves favorable variants and gradually builds fitness in a direction determined by the nature of the selection environment formed by markets and institutional factors. This implies that various involved actors create better adapted technologies (products and processes) through a learning process in the course of the evolutionary process. Thus as Rosenberg (1982, 49, see also Sahal 1981) argues:

> "what is really involved is a process of cumulative accretion of useful knowledge, to which many people make essential contributions, even though the prizes and recognition are usually accorded to the one actor who happens to have been on the stage at a critical moment."

Hence, the selection process is not just the execution of the unfit, but a creative process in which technologies are improved step by step, with contributions not only from producers of new knowledge but also from users. The definitions of 'better adapted' and 'fitness' crucially depend on what is required in the selection environment. We should not confuse 'optimal' with what 'survives.' There is no out-of-the-box definition of optimal. Instead, the requirements within the selection environment provide direction. While Nelson and Winter stress economic and regulatory requirements in markets, Basalla (1988) also adds religious, social, or other requirements that play a role in society at large and influence selection. Nelson and Winter emphasize profitability in their evolutionary theory, and particularly in their modeling work, because, as economists, they see markets as the main selection environment. But this does not necessarily follow from a natural selection theory. If we see the selection environment as multi-facetted, then multiple criteria are important in selection.

Outcomes of variation and selection processes become part of a technical regime, which is the underlying retention structure. Nelson and Winter (1977, 57) refer to the following classic example of a technical regime:

> "the advent of the DC3 aircraft in the 1930s defined a particular technological regime; metal skin, low wing, piston powered planes. Engineers had strong notions regarding the potential of this regime. For more than two decades innovation in aircraft design essentially involved better exploitation of this potential; improving the engines, enlarging the planes, making them more efficient."

The technical regime can be considered the genetic make-up (the genotype) of a technology expressing itself in products and processes (the phenotype) championed by different firms and sold on the market. Regimes are the source of stability of a technology because their rules are shared and reproduced. The introduction of the regime concept by Nelson and Winter is a crucial, but not always fully appreciated, step for applying evolutionary thinking to technological change. The development of an evolutionary account for discontinuity in technical change requires a specification of what discontinues. We need to define the equivalent of a species in technical change. In biology, one speaks of the emergence of a new species when organisms of that species no longer breed with organisms from the parental lineage. Retention is organized through genes, which are handed down between generations. In technological evolution sexual reproduction and retention in genes do not exist, and consequently in many evolutionary accounts of technical change it is somewhat unclear how to decide when a new technological species has arrived. To create a definition of 'species' in technological evolution, we propose, following Nelson and Winter, that a new technology forms a new species when a distinct regime emerges. We only broaden their technical regime concept by including institutional and market aspects needed to make the technical regime work. To highlight this difference, we prefer to use the concept of sociotechnical regime.[2] In line with insights from science and technology studies, we thus see technology as a set of aligned heterogeneous elements, which together provide a specific function such as transport.[3] Hence a regime is not only characterized by a set of rules that guide technical design, but also by rules that shape market development (e.g. user preferences) and rules for regulating these markets. In this understanding, a regime consists of a set of aligned rules that are carried by a range of actors (firms, users, governments) that together form a community. A sociotechnical regime thus binds producers, users and regulators together. The nature of the binding is not based on

[2] In the literature a range of technical regime definitions have proliferated. See, for example, Nelson and Winter (1977); Malerba and Orsenigo (1993); Rip and Kemp (1998); Kemp et al. (2001); Geels (2004). Although these authors differ in their formulation, they all share an emphasis on rules and the embodiment of these rules in practices, products etc. The main difference is that the original definition by Nelson and Winter was more restricted than later ones by Kemp, Rip, Schot and Geels. The latter are using a broader concept of regime, by not only focusing on the mind of engineers, firms and other technology actors, but also on regulatory structures, demand and broader social and cultural aspects. In this article, we follow this broader regime concept.

[3] This definition is derived from the way technology is defined within an actor network theory. See Callon (1987) and Latour (1987).

direct interaction among the actors, but on the participation in the production and reproduction of a sociotechnical regime. The regime rule-set is embodied in, among other things, shared engineering search heuristics, ways of defining problems, user preferences, expectations, product characteristics, skills, standards and regulatory frameworks. To conclude, a sociotechnical regime carries and stores the rules for how to produce, use and regulate specific products and processes. They perform the task of genes and define the boundary between technological species.

How, then, can we understand the emergence of new sociotechnical regimes in a natural selection model? To answer this question, we need to look at how the internal variability within sociotechnical regimes might link up with slowly changing selection pressures. We will first introduce the idea of variability and then discuss how slowly changing selection process might induce the establishment of a new sociotechnical regime. The internal variability within sociotechnical regimes received little attention in the seminal work of Nelson and Winter and Basalla. They tend to perceive a homogeneous selection environment.[4] Recently, it has been taken up by a number of evolutionary economists, among others by Saviotti (1996); Dalle (1997); Windrum and Birchenhall (1998); Frenken et al. (1999); and Nuvolari (2004).[5] Their work can be used to argue that within each sociotechnical regime firms produce a variety of products adapted to the particular needs of a range of different market niches. While these coexisting niches value particular elements of functionality, they evolve from the same global sociotechnical regime. In biology, Gould (1991, 58) introduced the idea of mosaic evolution to describe this branched development. There is no reason why this metaphor and the underlying ideas cannot be applied to technological evolution. A sociotechnical regime can consist of a range of different market niches. How much variety will proliferate depends on whether selection operates under conditions of resource scarcity (Aldrich 1979, 27–28). Homogenization will probably be particular strong in competitively saturated environments of finite resources. In such a situation, competitors will seek to out-compete each other, and hence reduce opportunities for local niches to persist. But competition might also be more relaxed, and allow for more variability and the existence of a number of market niches and designs, as Windrum and Birchenhall (1998) argue. Such variety might lead to regime transformation when one of the market niches is used by actors to exploit new opportunities provided by the slowly changing environment. In such a case, the improvements of the products operating within the market niche create substantial tensions within the sociotechnical regime. These tensions might take different forms: several firms might begin to doubt whether operating within the rules of the regime will help them to respond to future selection pressures and/or they might begin to see promising new opportunities due to the changing selection pressures. In this process, they might be stimulated by

[4] Kauffman (1995) recognized this aspect when he introduced the concept of fitness landscape in which a range of local optimums exist next to other (see also notion of adaptive landscape used in biology (Strickberger 2000).

[5] See also Carroll (1985) and Hannan and Freeman (1977) who use an evolutionary perspective to examine complete populations of organizations and the ways in which they change over time. They argue that, over time, generalist larger markets will emerge but not necessarily at the expense of specialist markets. They can co-exist and in this way make more resources available by avoiding direct competition. This is what Carroll calls resource partitioning.

governments and find willing users. If successful the new technology spreads over an industry and becomes more dominant through differential growth and through imitation, i.e. other technology actors start to produce the specific new variant as well. Over time and after many cumulative changes within the market niche, a new sociotechnical regime emerges and eventually substitutes for the old one.

Due to its gradual character, such a regime transformation is sometimes hard to discern, and may appear as optimization. A strong indication for a transformation is whether it is possible to establish ex-post a substantial change of knowledge base coupled to substantial changes in user preferences and regulatory structures. The definition of what is substantial will always stay a bit arbitrary, however, due to the fact that in this pattern the emergence of a new regime is continuous, cumulative, and emerges through adaptive change of longer sequences of small mutations, that emerge from regime internal market niches and is pushed forward by regime actors.

3 Punctuated equilibrium[6]

Some biologists have explicitly theorized the idea that some variations may be rather large, even while most variations are small. In their view, evolution is not only made up of small changes. While they agree that new species may emerge through the accumulation of many small changes, they see macro-variations as an additional possibility. One of these biological theorists is Richard Goldschmidt, who believes that macro-mutations, and not a collection of favorable but small mutations accumulating over a long period of time, were the driving force behind the emergence of new species (Goldschmidt 1940, cited in Goldschmidt 1998).

This idea has been taken up for technological evolution by Mokyr (1990a, 295). He maintains that there is ample evidence of the existence of discontinuous and often nonadaptive mutation in technological evolution.[7] While our definition of macro-inventions differs from the one introduced by Mokyr, we find his basic distinction between a micro- and macro-innovation useful. We emphasize that macro-inventions are defined by their lack of fit with the prevailing sociotechnical regime.[8] Following Mokyr, we see both types of invention as complements. Micro-inventions exploit the opportunities generated by a macro-invention, while such an invention makes it possible to overcome the diminishing returns of a series of micro-inventions.

Micro-inventions can be explained with standard economic concepts. They respond to prices and other institutional incentives, and develop through learning by doing and learning by using. They are similar to the small variations discussed in

[6] In biology, this notion has been introduced by Eldredge and Gould (1972); for an overview see Gould (2002), chapter 9.

[7] Mokyr (1990a: 294) gives several examples of macro-inventions in the late Middle Ages: windmills, spectacles, the mechanical clock, moveable type and the casting of iron. He also gives examples from the first and second Industrial Revolution: gas lighting, the breastwheel, the Jacquard loom, chlorine bleaching, and ballooning.

[8] Mokyr (1990a, 291) emphasizes that macro-inventions are ones without clear-cut parentage, representing a clear break from previous technique. To identify this break, the notion of regime is necessary; otherwise scholars such as Basalla (1988) will always be in the position to argue that some precursors do exist.

natural selection theory. Macro-inventions need a separate explanation, and do not respond to standard economic variables. Mokyr writes (1990a, 295):

> "Macro-inventions are more difficult to understand, and seem to be governed by individual genius and luck as much as by economic forces. (...) The timing of these inventions is consequently often hard to explain."

There are several macro-factors that may influence the supply of new ideas, e.g. religion, education, willingness to bear risk, and the social status of physical production in society. Another kind of explanation suggested by Mokyr is clustering, meaning that "the occurrence and timing of macro-inventions is partly explained by other macro-inventions."

Following R. Goldschmidt, Mokyr (1990a) refers to macro-inventions as "hopeful monstrosities." They are hopeful because they promise new technical and functional possibilities. They are monstrous because their early performance characteristics are typically low. This means that the development of a macro-invention into a viable, new technological species requires special circumstances. Mokyr emphasizes the importance of exogenous changes in the institutional and social environment. Such changes may create a temporary window of opportunity for further development of a macro-invention through a series of micro-inventions.

> "Macro-inventions are seeds sown by individual inventors in a social soil. (...) The environment into which the seeds are sown is, of course, the main determinant of whether they will sprout" (Mokyr 1990a, 299).

Macro-inventions are rare events, which, most of the time, are out-competed by existing, more efficient technologies, embedded and nurtured by a set of complementary technologies and vested interests. Only dramatic changes in the environment may change the rules of the game, and allow macro-inventions to survive.

The ideas of Mokyr fit into the so-called punctuated equilibrium perspective applied to technological evolution by technology management scholars (e.g. Anderson and Tushman 1990; Rosenkopf and Tushman 1994; Tushman and Anderson 1986; Tushman and Murmann 1998; see also Mokyr 1990b). They argue that technological development constitutes an evolutionary process punctuated by discontinuous change. For long periods of time, technological change is relatively stable, proceeding along technical trajectories ('era of incremental change'). These periods are punctuated by brief periods of rapid change. Such an 'era of ferment' is triggered by the appearance of a technological discontinuity.

Although this representation of the overall process is appealing, scholars advancing a punctuated equilibrium perspective do not have a clear theory about the emergence of technological discontinuity. They simply define technological discontinuities as offering "sharp price-performance improvements over existing technologies" (Tushman and Anderson 1986). But this is too simple, and against a lot of empirical evidence that shows that new technologies often emerge as 'hopeful monstrosities' and need indeed a lot of improvement before they can compete. Precisely for this reason, the idea of macro-mutations has been dismissed in biology. It is unclear how biological macro-mutations could survive in a hostile environment. Similarly, it is hard to see why firms and users would adopt a technology which is inferior to the one with which they already work. Hence, we think that an extra element should be added to the argument of Mokyr: the importance of destabilization of the prevailing sociotechnical regime *before* the macro-inventions can flourish. Our assumption is that the first impact of rapid and profound change in the external environment will be that actors (firms, governments, users) begin to doubt whether exploiting the rules of the prevailing regime will be productive.[9] Here, it is important to emphasize the importance of the perception of actors, because they might not (want to) see the change in circumstances. However, when they recognize it, support for the regime disappears, and it is precisely this development that creates the temporary rationale for investing in new and radical options. At first, several of them might flourish in different market niches, but eventually a new sociotechnical regime will emerge in a process of competition. These radical options do not need much protection (because the prevailing regime is in a process of downfall). They are first and foremost options that promise a new beginning. We propose to call the niches they exploit breakthrough niches.

One could expect that dramatic changes in the larger environment would not diminish the promise of only one sociotechnical regime, but will have an impact on many. Hence, we expect to see a clustering of emerging macro-inventions and breakthrough niches. This pattern fits the historical research by Mokyr (1990a) and also much of the data collected by long-wave analysts such as Freeman (1981) and others. In biological evolutionary theory, this phenomena is referred to as group-selection.

4 Market niche development

Levinthal (1998) uses a theory of Mayr (1963) developed within biology to propose a niche theory for technological evolution.[10] In his view, the basic mechanism is that a micro-invention is implemented in a new application domain isolated from the mainstream market. In this domain, very different selection criteria are present. The technical change involved will be minor (a small mutation as in natural selection theories), but the different selection criteria in the isolated market niche will trigger a divergent evolutionary trajectory. After several generations of products, this may

[9] For an insightful overview and conceptualization of changes triggered by extreme forms of change, see Suarez and Oliva (2005).

[10] In biology, most biologists accept that new species do not only emerge through adaptation, but usually also involve some form of isolation. In the allopatric theory developed by Ernst Mayr and others, new species emerge in geographically isolated niches or in niches operating at the periphery of a dominant existing ecosystem. These niches form the habitat for small populations that become isolated from their parental group at the periphery of the ancestral range. These niches lead to new developments because they provide a set of distinct selection pressures and thus lead to a divergent evolutionary path. Biological speciation in these small isolated populations may be rapid by evolutionary standards, because favorable genetic variation can spread quickly. In large central populations, on the other hand, favorable variations spread very slowly or change may be steadfastly resisted by the well-adapted population. Furthermore, when rare variants mix in large populations, the effect of the mutations may be watered down. So change in large populations tends to be small, directed to meet the requirements of slowly altering climates. Major genetic reorganizations, however, almost always take place in small peripherally isolated populations that can grow into a new species (see Mayr 1963).

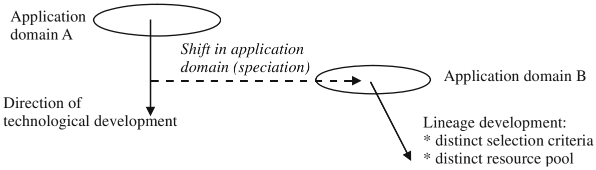

Fig. 1 Speciation in technological development (Levinthal 1998: 223)

eventually result in a new product that is substantially different from the original lineage (Fig. 1) and can begin to compete with the existing one. It is thus a model of delayed substitution. The view of Levinthal is comparable to the one advanced by Malerba and et al. (2003), who have pointed out that the launch of new technologies depends on the existence of fringe markets which the old technology does not serve well. Levinthal stresses that the process begins with micro-inventions, while Malerba and other emphasize new technologies. In our view, both options are valid: the potential of isolated market niches can be exploited by actors who advance micro- as well as macro-inventions.

Levinthal's idea of the role of niches comes very close to one advanced by Saviotti and others discussed above, who also emphasize the importance of market niches. Yet there is one main difference between the two types of market niches; the ones identified by Levinthal are shielded from the prevailing sociotechnical regime, or, in other words, they are isolated, while the niches discussed by Saviotti and others operate within this regime. We can see the difference between a natural selection and a market niche mechanism even better when we specify the nature of this isolation. Isolation can stem from cognitive, social and/or spatial distance.[11] Cognitive distance implies that regime actors do not consider the market niche as important for their products, mainly because it is too small and requires specific performance that cannot be served well by the various variants produced within the prevailing sociotechnical regime. Social distance can be part of this because products might serve specific social groups. Spatial isolation stems from application in a geographical area where specific conditions apply.

In a market niche pattern, the development of the technology within the niche will depend on the emergence of a sequence of micro-mutations. The speed of the sequence depends on the resources available in the market niche, and on the nature of the learning and networking processes among actors that support the technology. While novelty may be developed in one niche, its further diffusion usually depends on a process of invading other niches, gaining momentum and size, and through this process it begins to compete with the prevailing sociotechnical regime.[12] But head on competition is no necessity. New technologies may also continue to thrive in their

[11] For biological evolution, two types of isolating mechanisms have been identified: separation of populations through geographical separation (leading to allopatric speciation) and separation trough a range of mechanisms preventing gene exchange among populations in the same geographical location (leading to sympatric speciation) such as different courtship patterns, mating in different seasons etc. See Strickberger (2000).

[12] This is consistent with the important work of Gold (1983) and others who have shown that a diffusion curve consists of several separate diffusion curves, leading to a series of thresholds during the diffusion process.

own regime only, and co-exist for a long time with sociotechnical regimes that operate successfully in their own set of niches.

The competition between the new emerging technical regime that is developing into a new sociotechnical regime, on the one hand, and the replacement of the prevailing dominant sociotechnical regime can be represented with two dimensions: (a) the stability of rules, and (b) scale, i.e. the number and size of separate market niches, and thus social networks coordinated by particular rules. In diffusion studies, this is often measured in terms of the number of adopters. Figure 2 shows how these two dimensions play out in the overall pattern of emergence and further evolution of new sociotechnical regimes.

This third evolutionary pattern assumes that market niches are already present, ready to be entered by either a micro- or a macro-invention. The early steps in this pattern are not seen as problematic, because it is assumed that there is immediate viability and anticipated profitability in the specific market niche. Both assumptions need not always be true, however. Sometimes market niches do not exist, but are created based on a promise of future viability. In such a case, we speak of a technological niche.

5 Technological niche development

Analogies with biology have to be pursued with great caution because they may restrict our thinking. In particular, applying evolutionary analogies leads to an under conceptualization of ways in which the selection process can be anticipated and modulated by technology actors who push for certain variations. Variation need not be blind, as in Darwinian approaches, but can be directed. Such a Lamarckian view has been discarded for biological evolution, but it can be usefully applied to technological evolution, because the human beings involved have intentionality and aims when they work on innovations. In a Lamarckian model of evolution, technology actors try to develop technology, which allow the generation of products and processes that are fit to survive. So variation and selection are not independent. Actors anticipate on selection and work towards linkages between variations and

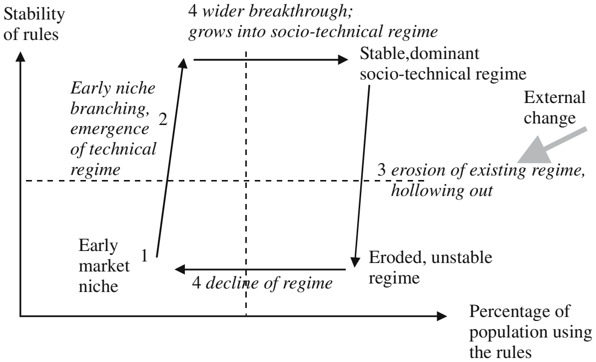

Fig. 2 Representation of emergence of new species and further breakthrough

selections. Variation comes subsequently pre-packaged in the right direction.[13] To some degree, we can already find this notion in the natural selection pattern described above, because we highlighted the role of sociotechnical regimes in innovation. So natural selection in our thinking provides a direction to the variation process, but it lacks the idea of anticipation and direct selection of a regime. In the natural selection pattern, sociotechnical regimes become selected indirectly. The notion of directed innovation was advanced in evolutionary economics by Giovanni Dosi, who suggested that direct selection of a technological paradigm (a notion comparable to the regime concept)[14] could be found in technological evolution. In his words:

> "Thus the economic and social environment affects technological development in two ways, first selecting the 'direction of mutation' (i.e. ex-ante selection of the technological paradigm) and then selecting among the mutations, in a more Darwinian manner (i.e. ex-post selection among 'Schumpeterian' trials and errors)." (Dosi 1982, 156).

However, while Dosi points to the importance of the difference between ex-ante and ex-post selection, he does not elaborate how Lamarckian selection operates and how variation and selection are linked. These issues have been elaborated in the quasi-evolutionary perspective, developed by Rip (1992, 1995); Schot (1992, 1998) and others (Hoogma et al. 2002; Kemp et al. 1998, 2001; Raven 2005).[15] This quasi-evolutionary perspective proposes that macro-mutations are nurtured in technological niches. A technological niche forms a protected space in which these inventions can be tried out and further developed as long as they do not compete and survive in mainstream markets. These protected spaces refer to real-life societal experiments with radical new technologies. The protection in technological niches comes from actors or constituencies that are willing to invest time and money in nurturing and developing a fledgling innovation. Since no market yet exists, the government is often heavily involved. The resources come from strategic R&D investments, public subsidies or special-purpose users, such as the military. One important reason actors are willing to protect a non-profitable innovation is the perceived importance for realizing societal and collective aims, often based on *expectations* or *beliefs* that the innovation will be viable in the future, either through technical improvements or anticipated changing selection pressures (Brown and Michael 2003; Van Lente 1993;

[13] Here, actors who anticipate and have intentions come in. Such actors are not present in biological evolution, and, therefore, Lamarck had to postulate some kind of intrinsic tendency in species to improve themselves. But this tendency is not part of the conventional wisdom in modern biology. The idea of directed change has resurfaced in biology, however, through the introduction of the idea of niche construction. Day Rachel et al. (2003, 81–82) have argued that organisms bring about changes in their local environment and "therefore new generations acquire not only genes from their ancestors but also an ecological inheritance, that is a legacy of a sub-set of natural selection pressures that have been modified by the niche construction of their genetic or ecological ancestors. Niche-constructing traits are more than just adaptations, because they play the additional role of modifying natural selection pressures, frequently in a directed manner, and in doing so they change the evolutionary dynamic".

[14] To stress the cognitive aspects, Dosi prefers to use the term 'paradigm'.

[15] They introduced the term 'quasi' because they see variation and selection not as independent but as coordinated to some extent.

Van Lente and Rip 1998). These actors adhere to diffuse scenarios about future use in particular markets. So the work on niches is guided by an expectation of future developments, for example, perceived threats caused by environmental degradation or market opportunities. Because of this expectation, actors operating in the niche may accept disadvantages in the present and invest resources in upgrading and development of a 'hopeful monstrosity.' Thus, anticipating new emerging or projected future demands, technology actors may exploit radical new technological opportunities, and create new technical regimes.

The technological niche construction literature implies that market for the innovation does not exist. This issue has received little attention in evolutionary theories of technical change.[16] The quasi-evolutionary niche theory addresses this issue, using recent insights from sociology of technology and innovation studies. The thrust of the answer is that new technologies, markets and users are *co-constructed* (Callon 1998; Coombs et al. 2001; Green 1992; Oudshoorn and Pinch 2003). In technological niches, learning processes are not only about technology but also about the articulation of user preferences and required changes in the government regulation. Selection thus becomes a quasi-evolutionary process of mutual articulation and the alignment of technology, demand and regulations; it is a process of making a technology and a specific environment mutually acceptable. Or to be more precise, technology and its environment are created in the same process. This kind of experimental exploration and articulation of new niches is also emphasized in recent business studies on radical innovation (e.g. Christensen 1997; Leonard 1998; Thomke 2003). Firms contribute and participate in societal experiments because they see them as important learning mechanisms. Lynn et al. (1996) call this a 'probe and learning process' and highlight the tentative logic behind it, as well as its stepwise and cumulative character.[17] When there is no clear selection environment, technological niches act as 'proto-markets' for new technologies, allowing interaction between users and producers in protected spaces. The nurturing and quasi-evolutionary learning processes may eventually result in the articulation of

[16] The lack of attention for dynamics at the demand side is increasingly recognized by evolutionary economists. Metcalfe (2001), for instance, gives the following diagnosis: "Although the development of a 'supply-side' evolutionary economics is by now well established, the corresponding lack of any 'demand-side' analysis is indeed remarkable. Given the emphasis in evolutionary thinking upon competition and structural change this is unfortunate to say the least. (...) It is an unfortunate feature of the Schumpeterian legacy that consumers are assigned too passive a role in the innovation process." And Witt (2001) notes: "The long term evolution of consumption and the growth of demand is difficult to explain on the basis of the rather sterile modern theory of preferences." For a presentation of the influence of consumer preferences, we also refer to Shy (1996).

[17] "These companies developed their products by probing initial markets with early versions of the products, learning from the probes, and probing again. In effect, they ran series of market experiments, introducing prototypes into a variety of market segments. (...) The approach at work in these cases might best be described as probing and learning. (...) Probing with immature versions of the product only makes sense if it serves as a vehicle for learning about the technology, and whether and how it can be scaled up, about the market, (...) and about government regulations and the need for regulatory approvals. (...). Probing and learning is an iterative process. The firms enter an initial market with an early version of the product, learn from the experience, modify the product and marketing approach based on what they learned, and then try again. Development of a discontinuous innovation becomes a process of successive approximation, probing and learning again and again" (Lynn et al. 1996).

a clear demand. In this way, a technological niche may develop into a market niche. When this is the case, the dynamic explored by Levinthal and others will take over.

6 Towards a niche theory

In evolutionary theories, radical technical change is often explored in two ways: either as a process that proceeds in small steps or as a process that is accomplished by a great leap forward which opens up new markets and creates new branches of industry. In this article, we have explained radical technical in a more differentiated and nuanced way, working towards a niche theory. Quite different principles might govern radical change processes. A first necessary step for such a niche theory is to define radical change. We propose to interpret it as a change of the underlying structure which regulates technical change. This structure we call a sociotechnical regime. Regimes produce dynamic equilibriums. They provide a space within which incremental innovation is nurtured, allowing adaptation to a slowly changing selection environment. The fit between the regime and the selection environment will never be complete, however, and regimes can resist changes and preserve to some extent nonadaptive technologies. How does a new sociotechnical regime establish itself? We distinguish four different mechanisms (evolutionary principles), where a mechanism refers to the underlying explanation of the process in terms of evolutionary processes, and the resulting pattern of change.

(a) Natural selection. In this pattern, a specific variant used in a regime internal market niche links up with a specific new trend in the selection environment. When the variant turns out to be successful, it might proliferate to other regimes' internal market niches and gain momentum through diffusion and imitation. This success, combined with the continuing change within the selection environment, could produce tensions between actors and rules of the sociotechnical regime. As a consequence, regime actors might loose faith in the viability of the dominant regime trajectories. In such a situation, regime actors might try to change some of the rules of the prevailing regime in order to create a better fit with the changing selection-environment. In some cases, this change might be fundamental and lead to the establishment of a new regime. In such a case, the rules of the regime begin to optimize in new direction. In other cases, it turns out to be possible to bend the rules in such a way that the prevailing regime survives. For example, the introduction of an electric vehicle might lead car manufacturers into the direction of a new regime when they focus their R&D efforts on optimization of environmental performance instead of boosting battery performance in order to make the electric vehicle comparable to the gasoline automobile.

(b) Punctuated equilibrium. In this pattern, a macro-invention breaks through due to a sudden and dramatic change in the selection environment. Consequently, the viability of the prevailing sociotechnical regime begins to look more bleak. Actors look for new alternatives, and try to exploit the emerging opportunities provided by the change. They become willing to invest in a range of multiple breakthrough niches. Through a process of incremental change within each niche and competition between niches, a new sociotechnical regime is punctuated.

(c) Market niche development. In this pattern, micro-inventions or macro-inventions are applied in market niches, isolated from mainstream markets. Because very different selection pressures operate in this market niche, technology development might lead to an adaptation process in a new, divergent direction. The new technology might also diffuse to other market niches, eventually leading to the development of a new sociotechnical regime. This regime may then begin to compete with the original sociotechnical regime by invading its mainstream markets.

(d) Technological niche development. In this pattern, macro-inventions are applied in technological niches. Technological niches are proto-markets created by a coalition of actors to test and develop new technologies with the aim to develop larger market niches. In this coalition, regime actors as well as other new actors might be present. In the long run, these niches threaten to replace the existing regime. These technological niches often lead to niche gestation, and never flourish beyond a number of pilot projects. Occasionally, they can become the basis for the development of a new sociotechnical regime. In such a case, they proceed through one of the three other mentioned patterns. A technological niche is not a mechanism that can produce a new technological species by itself. Still, it is an important mechanism because the three other patterns might be jumpstarted through the existence of technological niches.

The elaboration of four different mechanism and implicated patterns of radical change makes clear that different types of niches are present in technical change. (For a similar discussion, see also Raven 2005, 47–48). One important distinction is whether niches are internal to the prevailing sociotechnological regime or whether they are isolated from it. This isolation can stem from specific requirements operating in a market niche. It can also come from projected needs (expectations) and social demands often voiced by governments and societal groups that compel actors to invest in a proto-market or artificially created technological niche. A second important distinction is whether rules operating within niches are stable. In such a case, it is clear for producers and users what kind of product is needed. Both market niches internal to the regime and market niches isolated from the regime rules tend to be stable. This is different for technological niches where technology and user specifications are highly unstable. Using discussed distinctions of high/low stability of rules within the niche and high/low isolation or protection from the prevailing sociotechnical regime, we can define four types of niches (see Fig. 3):

1. A niche that features high stability and low protection/isolation from the prevailing sociotechnical regime. We call this a regime internal market niche;
2. A niche that builds on isolation from the sociotechnical regime and contains stable rules; We call this a regime external market niche;
3. A niche that is isolated from the sociotechnical regime and features no stability. We call this a technological niche
4. A niche that is not isolated or protected from the sociotechnical regime (due to the fact that the future of this regime looks bleak) but does not yet contain stable rules. We call this a breakthrough niche.

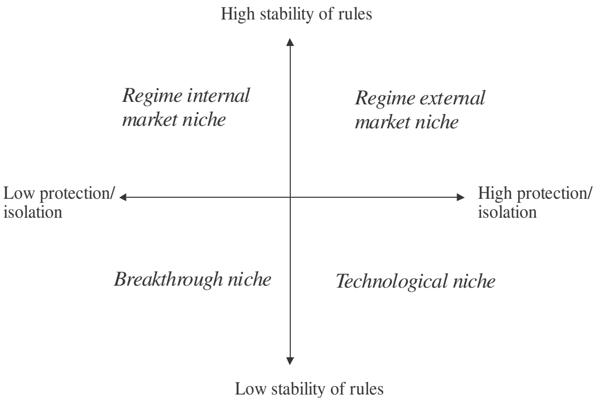

Fig. 3 Types of niches (adapted from Raven 2005: 48)

All four types of niches can become a seedbed for change. Whether this happens depends on the way developments in the niche link up with, on the one hand, developments within the dominant sociotechnical regime, and, on the other hand, changes within the broader selection environment outside the regime.[18]

Yet these processes of linking up are never automatic. An important difference between biological and technological evolution is that, in the latter, purposeful human actors (a technological community) intentionally try to solve perceived problems and seize perceived opportunities. They might also ignore problems and opportunities because they do not perceive them or they strategically decide to avoid addressing them (Grin 2007). The importance of intentions and strategies and thus agency in technological evolution implies that the pure Darwinian principle of natural selection, based on random variation, does not exist. Instead, the Lamarckian principle of directed variation, largely dismissed for biological evolution for lack of empirical evidence, plays a much larger and central role. Actors learn over time what works best for them in certain environments, and communicate and use this acquired knowledge to produce new variations and influence the selection process.[19]

However, at the same time, the outcome of the process over time is far from fully determined by the strategies used by the actors. Actors construct market or technological niches to get the world under control, but these newly created niches can become utterly useless as a result of unexpected new developments elsewhere. This is the second reason, next to the importance of the intentions and perceptions of

[18] The linking of niche, regime and broader selection environment changes has been advanced by us and others into a multi-level model (Rip and Kemp 1998; Geels 2002) and has been used for developing a taxonomy of transition pathways (Geels and Schot 2007).

[19] It is not necessary for technical evolution to choose for either a Darwinian or a Lamarckian theory. Lamarckism does not substitute or undermine Darwinism, but rather is a complement. New variants resulting from anticipation are still subject to natural selection, and there is nothing in Darwinism that necessarily commits us to define variation as entirely random in its origin. Finally, we might even theorize that the capacity for anticipation will spread due the process of natural selection because it produces fitter technologies. For a nice discussion on the issue of the relationships between Darwinian and Lamarckian theories, we refer to Hodgson (2001).

actors, why the coupling between niche, regime and broader selection pressures is never automatic and is hard to predict. When using an evolutionary account as proposed here, the analyses will never fail to deliver a fascinating story of the interplay between agencies in a changing context. To understand such interplay evolutionary theory is very helpful as long as it is enriched with sociological theory that provides insight into how actors create, nurture and sustain niches in response to emergent and often difficult to interpret change processes. The challenge before us is to explore the usefulness of the taxonomy for empirical research and formalize the theoretical analysis through simulation models, such as the ones developed by Windrum and Birchenhall (1998) and others.

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