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Appropriability, patents, and rates of innovation in complex products industries

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The economic theory of intellectual property rights is based on a rather narrow view of both competition and technological knowledge. We suggest some ways of enriching this framework with a more empirically grounded view of both and, by means of a simulation model, we analyse the impact of different property right regimes on the dynamics of a complex product industry, that is an industry where products are complex multi-component objects and competition takes place mainly through differentiation and component innovation. We show that, as the complexity of the product spaces increases, stronger patent regimes yield lower rates of innovation, lower product quality, and lower consumers' welfare.

Keywords: patents; appropriability of innovation; complex product industries; industrial dynamics

JEL Classification: O31; O34; L11

1. Introduction

From the point of view of economic theory, the protection of intellectual property has always been a matter of an uneasy balance between the divergent needs of providing sufficient returns and incentives to the production of innovations on the one side, and of promoting their quick social diffusion and therefore a prompt erosion of innovators' monopoly power to the advantage of consumers on the other side.

That a strong patent system is far from being the one and only necessary tool to achieve that balance was well expressed by Fritz Machlup back in 1958:

If we did not have a patent system, it would be irresponsible, on the basis of our present knowledge of its economic consequences, to recommend instituting one. But since we have had a patent system for a long time, it would be irresponsible, on the basis of our present knowledge, to recommend abolishing it. (Machlup 1958)

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Recently patents and intellectual property rights (IPRs henceforth) have become hot topics in the economic debate as the number of patents has increased exponentially and some profound institutional policy have determined the expansion of the patentability domain to include software, research tools, business methods, genes and artificially engineered organisms. The so-called ‘patent explosion’ has been documented and various explanations have been suggested (see for instance Kortum and Lerner 1998; Jaffe 2000; Lerner 2002; Jaffe and Lerner 2004; Hall 2005). Altogether a rather widespread consensus is emerging among many economists and practitioners alike that something is going wrong in the patent system that, instead of balancing contrasting needs and enhancing social welfare, is now mainly serving the interests of those companies holding large portfolios of patents (see Dosi, Marengo, and Pasquali 2006 for a critical discussion). The sharp increase in the strength of protection, the expansion of the domains of patentability and the loosening of standards for granting patents has *de facto* widely broadened the role of patents well beyond the purported aim to provide sufficient incentives to innovative efforts.

Patents are now used for strategic purposes, e.g. as means for entry deterrence, for blocking rivals’ innovations, for infringement and counter infringement suits against rivals, as ‘bargaining chips’ in the exchanges of technology among firms and to signal to financial markets likely streams of future profits (Jaffe 2000; Hall and Ziedonis 2001; Winter 2002). According to Harhoff et al. (2007) ‘Strategic use of the patent system arises whenever firms leverage complementarities between patents in order to attain a strategic advantage over technological rivals. This behaviour is anticompetitive if the main aim and effect of strategic use of the patent system is to decrease the efficiency of rival firms production efforts’ (p. 79). Under this perspective, it is noteworthy that ‘strategic patenting activity differs significantly from a situation of hold-up generated simply by the fact that different companies are specialized in the design and production of sub-components and they own complementary (and potentially blocking) patents’.¹

Empirical evidence on whether patent thickets, cross-licensing and owning of large patent portfolios on the part of incumbents – which is rather diffused in such sectors as computer, electronics and semiconductors – create or reinforce barriers to entry, is still not definitive. Hall and Ziedonis (2001), Cohen, Nelson, and Walsh (2000) and Shapiro (2000) suggest that the use of patents in portfolio exchanges among incumbents may deter entry into complex product industries. Strategies based on expanding patent portfolios as responses to hold-up problems have been recently analysed by Ziedonis (2004) for the semiconductors industry in the USA. Von Graevenitz, Wagner, and Harhoff (2010) show how patenting incentives are affected by competition for patent portfolios and complementarity of patents and ‘characterize how the degree of technological opportunity and the complexity of a technology determine the level of patenting of that technology’.

Not surprisingly, in some industries, top executives and representatives of industry associations are repeatedly expressing concerns for a state of affairs in which everybody is patenting more and more and asking for more protection just because the others do so, while believing that this race for more and stronger patents has little to do with incentives to innovate (Levin et al. 1987; Cohen, Nelson, and Walsh 2000; David 2002).

Bessen and Meurer (2008) find that: first, during the 1990s, the performance of the US patent system deteriorated as the private costs of patent litigation soared; second that ‘by the late 1990s the risk of patent litigation for public firms outside of the chemical and pharmaceutical industries exceeded the profits derived from patents’. This means that patents likely provided a net disincentive for innovation for the firms who fund the lion’s share of industrial R&D; that is, patents tax R&D; third, ‘for chemical patents, the private benefits of patents still substantially exceed the costs of litigation, indicating a net positive

incentive. On the other hand, for software, complex, and other patents the reverse is true, indicating a net disincentive’.

Particular concerns regard the so-called ‘complex product industries’. Complex products are those made of many different components whose production typically involves different underlying bodies of technological knowledge. Most artefacts in electronic, computer, ICT, automotive, aerospace, software industries belong to this category. Complex products, because of their multi-components and multi-technology nature, tend to involve multiple patents belonging to many different companies determining what has been called the ‘tragedy of the anti-commons’ (Heller 1998). For instance, ‘there are more than 400 patents that are essential to produce a DVD. And others have commented on the hundreds of patents typically related to a computer operating system or a PC. Yet the patent law remains mired in a nineteenth century paradigm of essentially *one patent, one product*’.

In complex product industries, patents are used to block rival use of components and acquire bargaining strength in cross-licensing negotiations (Gallini 2002; Ziedonis 2004). The presence of many property rights insisting on complementary components may hinder innovation and, in particular, systemic innovation which involves many components and modules. In fact, these industries are often characterized by fast radical innovation in the initial stages under weak IPR protection, whereas patents assume a prominent role in the firms’ competitive strategy in later and less innovative stages. Harhoff et al. (2007) recognize that in complex technologies, patents are a mainly defensive activity used to prevent hold-up and to acquire a stronger bargaining position. As to policy considerations, they underline the need of adopting a sectoral stance as to the evaluation of questionable behaviour involving patents, they suggest that competition authorities should be given the possibility of reducing the scope of individual exclusion rights and, finally, they observe the increasing importance of licensing agreements in complex technologies where patent thickets only can be unravelled with the help of licensing contracts.

So, for example, Bessen and Maskin (2009) observe that computers and semi-conductors while having been among the most innovative industries in the last 40 years, have historically had weak patent protection and rapid imitation of their products. It is well known that the software industry in the USA experienced a rapid strengthening of patent protection in the 1980s. They suggest that ‘far from unleashing a flurry of new innovative activity, these stronger rights ushered in a period in which R&D spending levelled off, if not declined, in the most patent-intensive industries and firms’ (Bessen and Maskin 2009, p. 2). In fact in such industries, imitation might be promoting innovation while strong patents might inhibit it.

Bessen and Maskin (2009) argue that this phenomenon is likely to occur in those technologies whose innovative activities are characterized by a relevant degree of sequentiality (each innovation builds on a previous one) and complementarity among different search lines. A patent actually prevents non-holders from the use of the idea (or of similar ideas) protected by the patent itself and in a sequential world full of complementarities, this turns out to slow innovation rates down. Conversely, it might well happen that firms would be better off in an environment characterized by easy imitation. Imitation would indeed reduce current profits, but it could also raise the probability of further profitable innovations to be realized. In addition, the generation of streams of diversified and complementary products, obtained by combinations of innovation and imitation, often increases the overall size of the market, increasing profit opportunities also for early innovators. As Paul David argues, IPRs are not necessary for new technologies, on the contrary, different institutional mechanisms more similar to open science might work more efficiently (David 1993, 2002).

Empirical evidence supporting these views can be found in a number of historical studies such as Nuvolari (2004) on steam technologies, Lamoreaux and Sokoloff (2000) on the glass industry in the USA, Cotterau (1997), and Sabel and Zeitlin (1985) on the silk industry. These studies suggest that collective invention settings in which competing firms share technical knowledge have proved to be a crucial source of innovation. Nuvolari (2004) suggests that the emergence of collective invention regimes and knowledge sharing might be traced back to a common awareness of negative effects of blocking patents or, for that matter, of tight IPR regimes in a context of cumulative technologies. Institutional regimes favouring practices of ‘technology sharing’ rather than appropriability have been the institutional settings that offered most support for streams of incremental innovation.

More in general, there seems to be in the standard pro-patent argument a lack of consideration of the specificities of sectors and technologies. As we will argue, the pro-patent arguments rests upon assumptions on the nature of technology and competition which are not, or at least not always, in line with the reality of (some) industries and technologies. Thus, the claim that without patents, imitators would rapidly cannibalize the innovator’s profits and therefore, anticipating it, no firm would have sufficient incentives to invest in costly R&D is not always correct.

In this paper, we develop a model of product innovation and industry evolution in complex product industries that explores the foregoing conjecture, showing that, indeed, strong patent regimes are likely to hinder rather than foster innovation. Such outcomes are driven by two major properties of technologies and markets for complex products. First, both innovative and imitative search are costly and difficult, with complementarities and interdependencies among components putting heavy constraints on possible search paths. If many of these possible paths are blocked by pending patents, very few opportunities for further innovation might be left open. Second, competition in these complex product spaces typically proceeds through the creation of sub-markets: demand is heterogeneous and firms can diversify products by offering different combinations of components and characteristics. Competition is not a winner-takes-all process, but is mainly a never-ending creation of new sub-markets.

The way we model our complex product space allows us to parameterize in a straightforward manner the main features of a patent regime. In particular, we first represent products as systems composed of a number of discrete components. We then endow the products’ space with a metric structure that allows us to compare two products and identify their degree of diversity as measured by two different notions: vertical and horizontal diversity. With ‘vertical diversity’ we refer to the required minimum difference (distance) of different products’ components. This will be measured by the average of the distances between single components. With ‘horizontal diversity’ we shall refer to the minimum number of components on which a product must differ from an existing one in order to be recognizably different. This will be measured by the share of components which are not identical. With ‘coarseness’ we shall refer to the possibility of establishing IPRs on entire products, on products’ sets of components or on single components. We show that as the complexity of the product space increases, stronger patents regimes, that is regimes characterized by larger vertical and horizontal amplitude and lower patent coarseness, yield lower rates of innovation, lower product quality and lower consumers’ welfare. In particular, if product complexity is low, a strong patent regime will increase social welfare as higher prices and concentration will be more than compensated by higher innovation and product quality. On the other hand, if product complexity is high, a strong patent system, in addition to leading to higher prices and higher concentration, will also be the cause of lower rates of innovation and product quality growth.

Our model is evolutionary in spirit, but whereas most evolutionary models focus on process innovation (cf. Winter 1993 or Vallee and Yildizoglu 2006), we exclusively model product innovation, i.e. the generation of new combinations of components. As demand is differentiated, new products create new sub-markets only loosely competing with the existing ones. We show that IPRs do indeed have an impact not only on the incentives to do research and development, but also on the directions in which research moves and that the directions induced by strong IPR arrangements might be far from optimal in a dynamic perspective. Moreover, we show that, other things being equal, any one IPR regime has a different impact upon innovation rates depending on technological opportunities and the complexity of the underlying technological space. To the best of our knowledge, the present contribution is the first one having such characteristics.

The model we present is admittedly sketchy and only focussed on how the patent system works as an incentive mechanism aimed at fostering innovation. We thus leave out of our analysis a whole bunch of relevant issues such as cross-licensing, pooling and, in general, the issue of markets for technologies. It goes without saying that the latter issues have a wide potential effect on competition and innovation (Shapiro 2000). Our model is, however, one step behind the consideration of these effects and its added value is on offering a precise measure of the relation between welfare-enhancing properties of patent systems as measured by their strength, products' complexity as measured by their decomposability/modularity degree and patent coarseness measured by the amplitude of products' modules they can be defined on.

The paper is organized as follows: in Section 2, we develop our interpretative framework. In Section 3, we introduce and discuss the model. In Section 4, we simulate the model and present the main results from simulations. Finally in Section 5, we highlight the major conclusions and draw some tentative policy implications.

2. Patents, innovation, and competition

The economic foundations of both theory and practice of IPR protection rest upon a standard positive externalities, market failure argument. The argument's premise is: since knowledge bears some features of a public good,³ it will be underproduced and will receive insufficient investment. While the argument's conclusion – largely based on a Coasian perspective – is that the attribution and enforcement of well-defined private property rights is the key to the solution of the externality problem (Coase 1960).

However, in the case of knowledge there are two important *caveats*. First, as far as knowledge is concerned, only half of the standard positive externality story seems to hold. Knowledge externalities may indeed generate insufficient investment in its production, but the danger of excess exploitation cannot exist for a resource-like knowledge which is not depleted with use. On the contrary, multiple uses of knowledge are likely to generate increasing returns from learning and knowledge cumulation. Property rights do not appear as the right legal and institutional framework to solve the problem, if any, of knowledge, as the economic foundations for exclusion right are simply not there. Moreover, when granted on truly innovative knowledge, exclusion generates a particularly serious monopoly problem because by definition truly innovative knowledge is unique, does not have close substitutes and is often a key factor of production.

Second, one of the most significant advances in the fields of the economics of innovation has been precisely the identification of the specificities of technological knowledge in a strict sense as distinguished from sheer information. Technological knowledge, well beyond any description in terms of well-defined blueprints, involves procedures of a much more

tacit nature, often embodied in organizational practices and specific to each technological paradigm (Winter 1982; Dosi 1988). For our purpose here, a fundamental implication is that any analysis of the conditions for appropriation and diffusion of knowledge cannot abstain from considering the specific features of the knowledge itself. Knowledge complexity, cumulativeness, tacitness, replicability, and degree and location of technological opportunities are fundamental dimensions for understanding the dynamics of productive knowledge (Winter 1987).

The diversity of knowledge characteristics is reflected also into diversity of appropriability regimes. The patent monopoly is one such form of appropriation which is neither the most effective nor the most utilized in many sectors (Levin et al. 1987; Cohen, Nelson, and Walsh 2000). Teece (1986) argues that an innovation is rarely an isolated and well-defined entity, while the appropriation of its economic value is dependent upon a series of complementary assets whose control is often more fundamental for reaping the economic returns to innovation than the regime of legal protection of the rights of the 'innovator'.

How do appropriability conditions in general and the regimes of IPR protection influence the rates and the directions of innovative search? Several historical instances seem to suggest that above a minimum threshold appropriability conditions and, more so, IPR regimes exert hardly any influence on the rates of innovations. Thus, one observes many important innovations that, in spite of not being patented (or patented under very weak patent regimes) have most definitely produced considerable streams of economic value both to the innovator and to society. The technologies at the core of ICT are a case to the point. The transistor, while being patented from Bell Labs, was liberally licensed as a consequence of antitrust litigation and pressure from the US Justice Department, and more in general the early growth of the semi-conductor industry had been driven to a good extent by public procurement under a weak IPR regime (Granstrand 2005). The software industry, certainly quite a profitable one, similarly emerged under a weak IP regime. The telecom industry was largely operated by national monopolies until the 1990s who were undertaking also a good deal of research, and IPRs played little role in the rapid advance of technology in this industry. Mobile telephony also emerged under a weak IPR regime (until the late 1980s).

What about the directions of innovative search? Circumstantial evidence suggests that in the presence of complementarities among components and diverse pieces of knowledge, IPR regimes are likely to influence innovation trajectories. In particular, if technological opportunities are not mutually independent then, by foreclosing some firms' research in some directions, patents may on the whole hinder research rather than stimulate it.

In this paper, we analyse the general case of interdependencies in technological knowledge. We show, also building upon some previous work of ours (Marengo and Dosi 2005; Marengo, Pasquali, and Valente 2005; Dosi, Marengo, and Pasquali 2006), that the breadth and width of IPRs is not immaterial in determining which kind of innovation undergo market testing and selection processes. As we shall see, one dimension that appears to be crucial in our analysis is what we call the 'coarseness' of patents, i.e. whether IPRs are defined on product systems in their entirety or on components, sub-components, and so on with finer and finer objects of IPRs. In a Coasian perspective, the latter solution (i.e. very finely defined property rights) should in principle – if it was not for transaction costs – increase efficiency, in our framework, instead it decreases the number of technological opportunities which can be created and exploited.

A complementary issue, we are going to investigate concerns the function of markets. Nowadays a significant share of innovations are product innovations whose main purpose and effect is to create new sub-markets (Klette and Kortum 1984; Sutton 1998; Klepper and Thompson 2006), which only loosely compete with the existing ones. The perfect

competition benchmark seems therefore a quite inappropriate description of the actual mechanisms of technological competition. Again, the pace and directions of the creation of submarkets may be highly influenced by the definition and attributions of IPRs and this effect – we will argue – might be more important than the one measured against some benchmark of static efficiency.

All in all, the institutional attribution of property rights (whether efficient or not in a static allocative perspective) may strongly influence the patterns of technological evolution in directions which are not necessarily optimal or even desirable. In this sense, any question about the appropriate level of IP protection and degree of appropriability is better grounded on a theory of innovative opportunities and productive knowledge (issues on which the theory of allocative efficiency is rather silent: cf. Winter (1982) and Stiglitz (1994) from different angles).

In the next section, we outline a simple simulation model in which we try to capture at least some of the features of productive knowledge and competition we have briefly outlined above and use it to explore the consequences of different patent regimes.

3. The model

3.1. Technology space

We model products as systems made of n discrete components $\{x_1, x_2, \dots, x_n\}$. Each component can take one out of a countable set of values $x_j = \{0, 1, \dots\}$. Values account for different types of components (e.g. CPU types, wing shapes, brake cooling systems, etc.) and at a higher value for a given component corresponds a better type in a mere technological sense (e.g. a faster CPU) and considering the component as ‘stand-alone’, meaning that, as we will see, a better component does not always increase the overall performance of the product, but only when all components are co-adapted. Finally, let X be the set of vectors $x^i = [x_1^i, x_2^i, \dots, x_n^i]$ with $x_j^i = \{0, 1, \dots\}$ that contains all possible products.

We endow the products set X with a metric structure that easily allows to compare products and identify their degree of diversity. In particular, we define *horizontal* and *vertical* diversity as our two measures and we will use them to map the horizontal and vertical scope (breadth) of patents. The horizontal diversity between two products x^i and x^j is given by the share of their components which are not identical:

$$H(x^i, x^j) = \frac{\sum_{v=1}^n h(x_v^i, x_v^j)}{n}, \quad (1)$$

where $h(x_v^i, x_v^j) = 0$ if $x_v^i = x_v^j$ and $h(x_v^i, x_v^j) = 1$ if $x_v^i \neq x_v^j$.

Conversely, we define vertical diversity as the average of the distances between single components:

$$V(x^i, x^j) = \frac{\sum_{k=1}^n |x_k^i - x_k^j|}{n}. \quad (2)$$

Performance of a product is a function of the specific combination of single components. Performance is thus measured by a map $f : X \mapsto R^+$ which maps each member x of the products space X into the set of non-negative reals as follows:

$$f(x) = \sum_{i=1}^n \left(x_i - \sum_{j=1}^n (\epsilon_{i,j} \cdot |x_i - x_j|) \right) + K, \quad (3)$$

where $\epsilon_{i,j} \in [0, 1]$ represents how the performance contribution of component i is affected by component j and K is a constant.⁴

Product performance changes as a consequence of two different, but interrelated reasons, namely a change in the technical characteristics of the single components and via interdependencies across components. The latter also determines the ‘complexity’ of the product space, that is the presence and extent of the interdependencies among the components forming a product. The coefficients $\epsilon_{i,j}$ capture such complexity. If $\epsilon_{i,j} = 0 \forall i, j$, the product space does not present any interdependencies, thus an improvement in any component always determines an improvement in the product’s performance irrespective of the state of the other components. If, on the contrary, $\epsilon_{i,j} \neq 0$, the contribution to performance of component x_i depends non-monotonically also on the state of component x_j .

As to the extent of such interdependencies, single components may interact with just a few others, or vice versa all of the n components may interact together. A special but important case is when interactions have a modular or quasi-decomposable structure (Simon 1969; Baldwin and Clark 2000), i.e. when the set of components is divided into subsets (modules) characterized by strong interactions within themselves and weak or no interactions with other subsets (modules) (see Marengo and Dosi 2005; Marengo, Pasquali, and Valente 2005 for a more detailed and formal treatment of this case).

The coupling between each element $x \in X$ and its performance value defines what we call ‘performance surface’. The features of such surface define also the *difficulty* of the innovation process. At one extreme, in the case without interdependencies, autonomous, local improvements (i.e. on single components) can generate a steady stream of successful (i.e. performance increasing) innovations and the performance surface is characterized by a high correlation among the performances of similar products. Only in this case can innovation be effectively decentralized and innovators can specialize on single components or small modules whereas coordination is effectively ensured by some market-like selection mechanism based on a ‘decentralized’ performance evaluation. At the other extreme, we have the case of widespread non-monotonic interactions which generate uncorrelated performance surfaces. In these circumstances, autonomous local changes tend to be ineffective and innovation requires coordinated search on many, possibly all, components together and deliberate re-designing of the system. In this case, decentralization is likely to be ineffective (see Marengo and Dosi 2005 for a more detailed and formal exploration of the consequences for division of labour and governance structures).

Finally, we assume that each product type x^i has an associated variable cost of production c_i which is an increasing function of performance with some random error:

$$c_i = a + bf_i + \epsilon_i, \quad (4)$$

where ϵ_i is an idiosyncratic normally distributed error. For the sake of simplicity, we set fixed costs equal to zero.

3.2. Demand

Demand depends upon prices, performance and positioning of products in the space of product characteristics. In line with Anderson, De Palma, and Thisse (1989) and their discrete choice model over products defined in the space of characteristics, we assume there exists a finite set C of consumers. Each consumer purchases at most one unit (possibly none) of a differentiated good. Each consumer has an ideal product profile, i.e. her type $t^i = [t_1^i, t_2^i, \dots, t_n^i]$ with $\sum_{h=1}^n t_h^i = 1$, defined by an ‘ideal combination’ of characteristics the consumer would like to find in the product.⁵

A consumer's utility depends upon four factors, namely the overall product performance, the distance between the product profile and the consumer's ideal one, the price and a normally distributed error. We assume that the elasticities of utility with respect to the first three factors are consumer specific.

The utility of consumer i buying product x^j is given by

$$U_i(x^j) = Af_j^{w_i^f} \left(\frac{1}{p_j} \right)^{w_i^p} d_j^{w_i^d} \epsilon, \quad (5)$$

where f_j and p_j are performance and price of product x^j , d_j is the distance between the product's profile and consumer's i type t_i , $\epsilon \sim \mathcal{N}(1, \sigma)$ is a normally distributed error. Finally, w_i^f , w_i^p , and w_i^d are consumer-specific elasticities with respect to performance, price and distance and A is a constant.

The distance $d_{j,i}$ of product j from consumer i 's ideal profile is computed as

$$d_{j,i} = \sum_{h=1}^n x_{j,h} \cdot t_h^i. \quad (6)$$

We call the market space of product x^j the set of consumers:

$$M_{x^j} = \{i \in C; U_i(x^j) \geq U_i(x^h), \forall h \neq j\}. \quad (7)$$

Demand for product x^j is thus given by the cardinality of the set M_{x^j} .

We assume that consumers are potentially utility maximizers, but also that there is some inertia in their decisions at each discrete time. We thus suppose that some proportion of consumers⁶ compute their preferences over all available products, rank them and choose accordingly, while all the other consumers simply reiterate the same purchases of the previous period.

3.3. Firms

Firms produce only one type of product in the amount demanded by the market and have R&D investment and output prices as their control variables. Concerning the related behavioural rules, in the case of R&D investment decisions, we follow the phenomenological generalizations of evolutionary models of technical change and industrial dynamics (Nelson and Winter 1982; Winter 1984, 1993) and assume that firms take routine decisions by applying rules-of-thumb, and in particular that they invest in R&D a given share of their gross profits.

As to price decisions, we assume that firms are more rational than usually assumed by evolutionary models and make the hypothesis that they are myopically rational. In particular, we want would-be patent holders to correctly know their rent-extracting potential and endow them with the ability to fix a price that, even with some inertia, gives them all the profit generated by monopoly and invest in further R&D accordingly. Such behavioural assumptions are taken in order to pre-empt the argument that our results depend upon the bounds we may put on agents' rationality and/or on the heavy restrictions on information and access to it. Thus, we want to build an *a fortiori* argument wherein our conclusions would apply, even more so if the most far-fetched assumptions on rationality and information would be dropped. In this respect, a crucial ingredient of the pro-patent argument is the purported link between high monopoly profits and high R&D investment yielding (in probability) more innovations. We want to fully preserve this link in our model, even at the cost of less realism.

3.3.1. Price decisions

At each discrete time, prices are set by all firms launching a new product and also by a random subset of firms offering an incumbent product that are allowed to re-compute their prices. All other firms keep their prices unchanged. Firms allowed to set or re-set their prices may access Walrasian demand schedules of all consumers (hence they are able to access their whole preference schedule), aggregate them and set the profit maximizing price, on the assumption that all other firms keep their prices unchanged.

3.3.2. R&D and innovation

Firms invest a share of their gross profits (for simplicity, we exclude external financing) in R&D. There can be two types of R&D investment: imitative R&D and innovative R&D. Let us call r_i^M the share on profits of the former and r_i^I the share of the latter for firm i . Total R&D expenses will be $(r_i^M + r_i^I)\pi_i$ where π_i are firm i 's gross profits. For the time being and for the sake of simplicity, we exogenously fix both coefficients r^I and r^M to 0.5.⁷

We model imitative search in a straightforward way: the imitator can observe the characteristics of the product of the most profitable firm and imitate part of it. The number of components which can be imitated is a function of the money invested in imitative R&D, i.e. $r_i^M\pi_i$.

As to innovative R&D, firms may have more or less specialized R&D activities, meaning that they can concentrate their research effort only on one or a few components or make extensive search on the entire vector of components. We call the scope of R&D of firm i , $1 \leq \theta_i \leq n$ the number of components on which money for innovative R&D is spent. Given the amount invested in R&D and the scope of research, firms engaged in innovative R&D make random draws in the space of components in the neighbourhood of their current value, where the size of the neighbourhood is directly proportional to the money invested and inversely proportional to the scope θ_i .

The routine for innovation is implemented as follows (patent infringement and patentability tests will be discussed in detail in the next subsection): optimal price, corresponding expected profits and expected sales are computed for the current product. A module (i.e. a subset of components) of the vector representing the product is randomly chosen and the value of some of its components is increased. As already mentioned, the number of components which are improved is determined by the scope parameter θ_i and the size of possible improvements is proportional to the firm's R&D investment. After a check on whether the new product infringes or not on an existing patent, performance, optimal price, expected sales and profits are computed knowing the demand schedule of all consumer and under the assumption that all other firms will not change their behaviour. If the product has higher expected profits or equal profits and higher performance it is adopted. On the other hand, if the innovation is not expected to increase profits (or performance with equal profits), the firm sticks to the old product.

The routine for imitation is performed only if there are firms with higher profits, otherwise the firm does not attempt any imitation. When a firm imitates, a target firm is chosen with probability proportional to profits among those with higher profits. Then a module is randomly chosen among those forming the target product to be imitated. Being x_h^i the h th component of the imitating firm's product i and x_h^j the same component of the target firm product j , all distances $(x_h^j - x_h^i)$ are computed and x_h^i is increased by 1, starting from components for which the distance from the target firms is higher. In case the new product does not infringe a patent, its performance, optimal price, expected sales and expected profits are computed. Again, as in the case of innovations, the new product is adopted (and

possibly patented) if and only if it gives higher expected profits or equal profits and higher performance.

3.4. Patents

In the framework outlined so far, one can easily model patents and their main characteristics. When a firm introduces a new product x^i it can immediately (and costlessly) obtain a patent on it if and only if the product meets the patentability standards, i.e. if it differs ‘enough’, both horizontally and vertically, from all products already protected by a patent. In particular, two conditions have to be met for product x^i to be granted a patent:

- (1) $H(x^i, x^*) \geq H_P$ for all products x^* holding a patent, and
- (2) $V(x^i, x^*) \geq V_P$ for all products x^* holding a patent.

The parameters H_P and V_P are called, respectively, the horizontal and vertical patentability standards and are parameters set by legal norms and by rules and practices of the patent offices.

If a product x^* is patented, we assume that no other firm can produce any product which is similar ‘enough’. Thus any new product x^j has to satisfy the following two conditions in order to be marketed:

- (1) $H(x^j, x^*) \geq H_A$ for all products x^* holding a patent, except those patented by firm j itself;
- (2) $V(x^j, x^*) \geq V_A$ for all products x^* holding a patent, except those patented by firm j itself.

The parameters H_A and V_A are called, respectively, the horizontal and vertical amplitude of patents and are also the outcome of legislation and judicial practice.⁸ Such amplitude parameters are important indicators of the strength of the patent system: the ampler a patent the stronger the protection from imitation and the stronger the legal monopoly power granted to the patent holder. Notice that, in general, $H_P \neq H_A$ and $V_P \neq V_A$, that is the requirements for obtaining a patent and those for legally selling a product without infringing an existing patent may be different, if anything because usually different institutional subjects are called to decide on either question, e.g. the patent office and a court.⁹

Finally, all patents have a finite life as they expire after a number L_P of iterations.

3.4.1. ‘Coarse’ versus ‘fine’ patents

Our model of products as complex systems of interdependent components allows us to tackle the issue of the coarseness of patents. Patents are ‘coarsest’ if they are granted only on the whole product, if instead they are granted on each single component they are ‘finest’. In the latter case, suppose that firm i introduces a new value for component x_h^i and patents it. As a consequence, no other firm will be allowed to market a product whose h th component x_h^j is within a distance $|x_h^j - x_h^i| < V_A$ from it, nor to patent a product containing a component x_h^j within a distance $|x_h^j - x_h^i| < V_P$ from it.

Finer patents place more restrictions on imitation. In fact, whereas a patent on a single component x_h^i prevents all other firms from selling products containing that or a similar component, if patents are instead granted only on whole products, that same component could be sold by other firm without breaching the patent, provided it is part of a product that on the whole is sufficiently diverse from the patented one. Thus, granting finer patents also witnesses an institutional framework more inclined to providing stronger IPRs protection.

As already mentioned above, in a Coasian perspective and abstracting from transaction costs, finer property rights should inevitably lead to higher efficiency as they increase the internalization of knowledge externalities. However, we will show that in our model the fragmentation of property rights is generally a source of long-run loss of social welfare and decreases the speed of innovation.

4. Simulation results

The model outlined in the previous section is basically driven by innovation in components and their interactions which yield the dynamics of the industry. In the following, we shall present a few simulations¹⁰ highlighting some fundamental properties of the model. For the sake of clarity, we begin with a synthesis of the main results, then we provide some details for each of them in the following subsections.

The main results can be summarized as follows:

- *product complexity* is an important cause of inefficiency for a strong patent system. In our model, innovating firms are capable of exploiting their competitive advantage, reap high profits and re-invest them in further R&D activities. If product complexity is low, this vicious mechanism determines indeed a loss of efficiency due to prices which persistently remain above the competitive level and determines higher concentration, but in the long run, these effects are more than outweighed by higher rates of innovation, higher product quality and higher overall consumers' welfare. If on the contrary product complexity is high a strong patent system, in addition to leading to higher prices and concentration, is also a cause of lower overall rates of innovation and product quality growth.
- *patent coarseness* is an important institutional feature that determines the efficiency of patent protection. Are patents granted only on whole products or also on single components? We show that in the latter case, patents are much more likely to generate long-run inefficiencies even in environments characterized by low complexity.
- moreover, granting 'fine' patents on single components or small modules, causes a distortion of market selection in favour of firms with specialized and narrow R&D against those with broad R&D scope. In complex product spaces, this produces early lock-in into suboptimal products.

4.1. The effect of product complexity

The first question we address is whether product complexity is a factor affecting the efficiency of different patent regimes. We mentioned above that concerns have been raised on the possibility that in complex technologies a strong patent system may stifle technological progress because of such phenomena as tragedies of the 'anti-commons', patent thickets and the like. Our model allows to test this concern in a more fundamental sense and within a dynamic model of industry evolution.

We ran a series of simulations in which we tested the properties of different patent regimes in industries characterized by either low or high product complexity. Figures 1–5 report the time series of some key variables in an industry without interdependencies among product components, with or without the possibility of patent protection (holding equal all other parameters).

In the absence of product interdependencies, patents do indeed, in our model, increase the overall efficiency and welfare. This is essentially due to the assumption that firms tune their R&D investment on an unlimited knowledge of their returns. Although our firms do

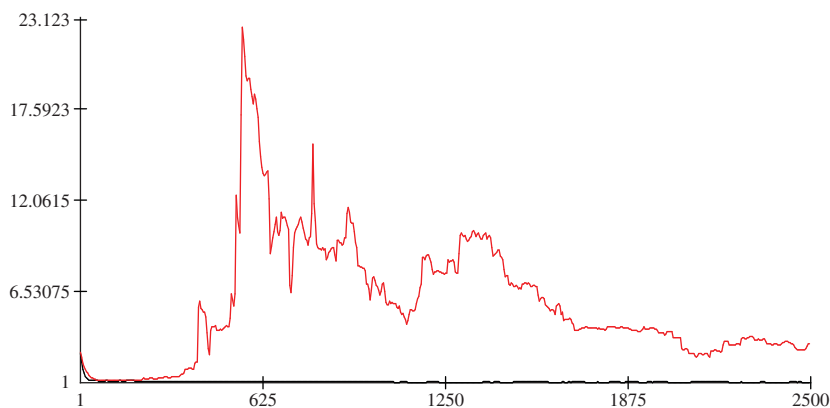


Figure 1. *Average price*, with patents (red) and without patents (black) ($N = 10$, no interdependencies).

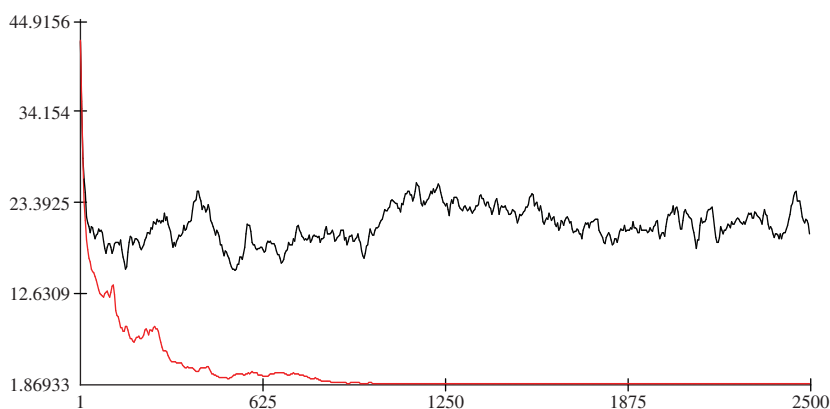


Figure 2. *Industry concentration* (inverse Herfindahl index), with patents (red) and without patents (black) ($N = 10$, no interdependencies).

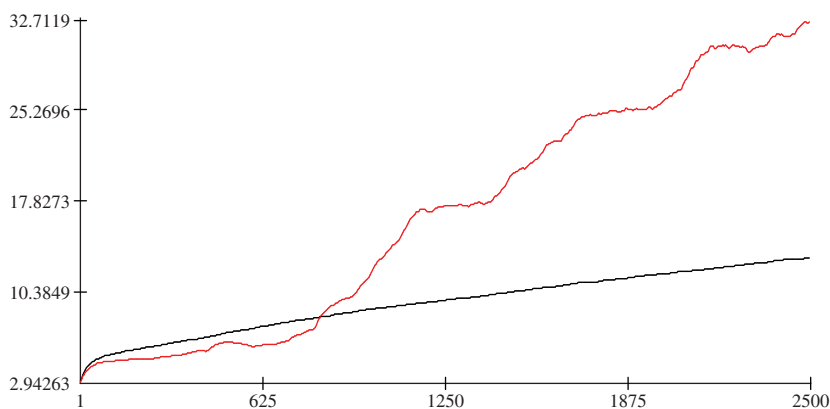


Figure 3. *Consumers' welfare*, with patents (red) and without patents (black) ($N = 10$, no interdependencies).

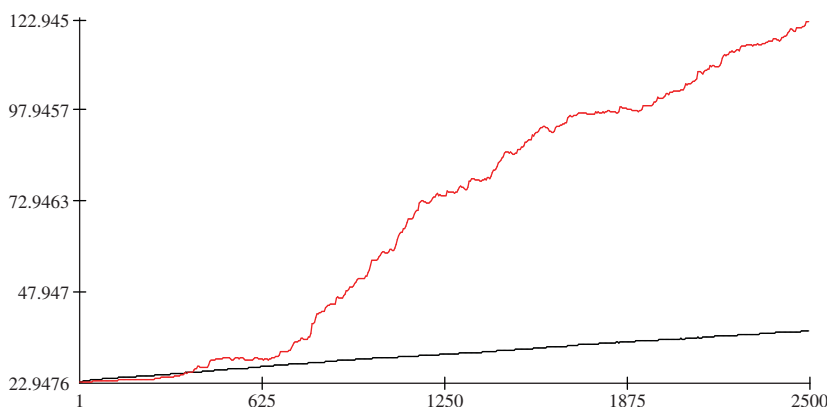


Figure 4. *Average product quality*, with patents (red) and without patents (black) ($N = 10$, no interdependencies).

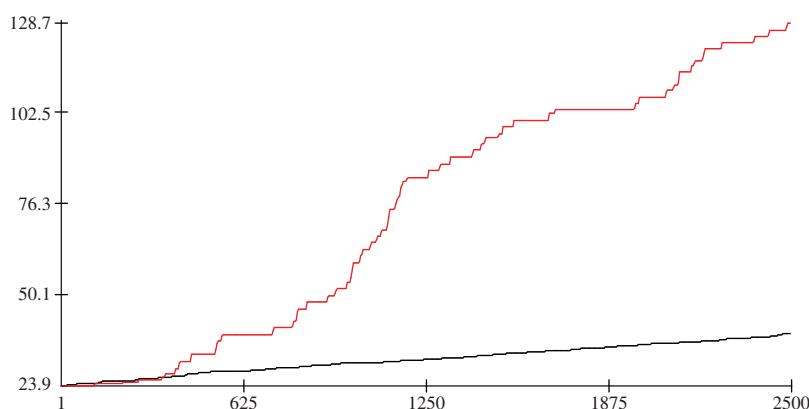


Figure 5. *Maximum product quality*, with patents (red) and without patents (black) ($N = 10$, no interdependencies).

not choose the level of R&D investment with forward looking rationality, but by routinely investing a share of their profits, the (correctly estimated) higher profits that can be reaped by innovators lead to higher R&D and further innovation.¹¹ Overall, product quality rapidly increases and so does social welfare, in spite of higher prices and concentration. Notice also that in the absence of interdependencies, product innovation is relatively ‘simple’, in the sense that each component can be improved independently of the others: putting more resources into R&D therefore increases the probability of finding some better components, and better components inevitably result into better products because of the separability of the product system.

Figures 6–10 present the same variables for an industry characterized instead by high technological interdependencies. It can be noticed that in this case, in the absence of patent protection, not only are prices and industry concentration lower, but also innovation and product quality show a consistently higher level and therefore consumers’ welfare is obviously higher without patent protection.

Given high interdependencies, innovation is far more complex a process. Innovative paths are fewer and far between than in the case without them: not only better components

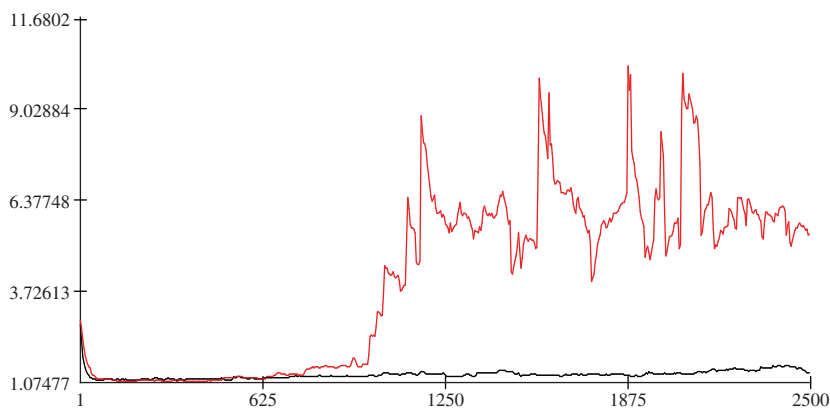


Figure 6. *Average price*, with patents (red) and without patents (black) ($N = 10$, high interdependencies).

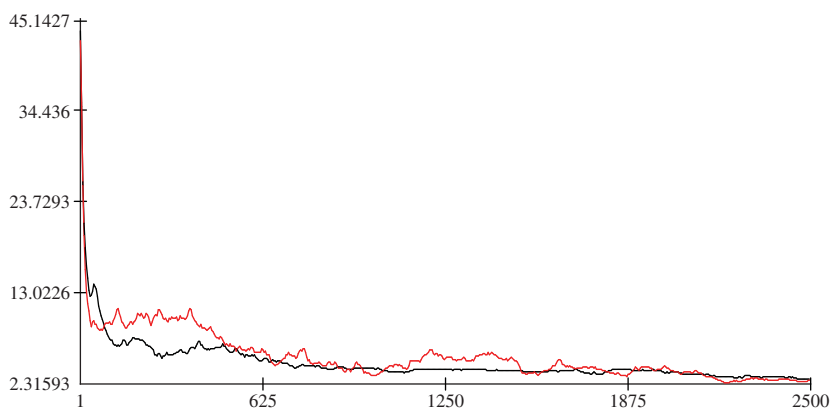


Figure 7. *Industry concentration* (inverse Herfindahl index), with patents (red) and without patents (black) ($N = 10$, high interdependencies).

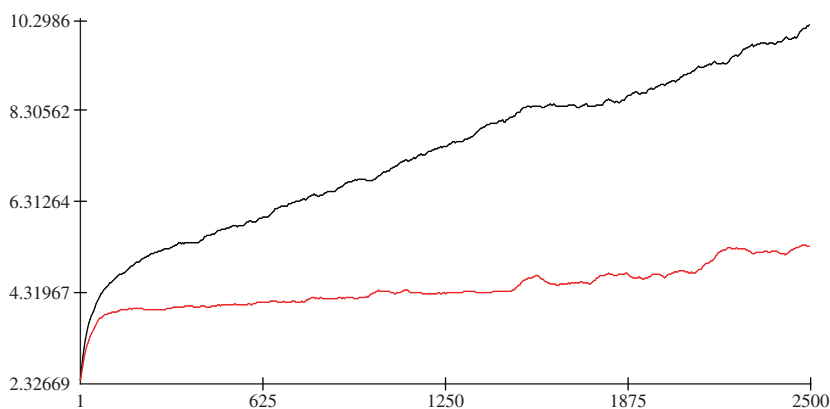


Figure 8. *Consumers' welfare*, with patents (red) and without patents (black) ($N = 10$, high interdependencies).

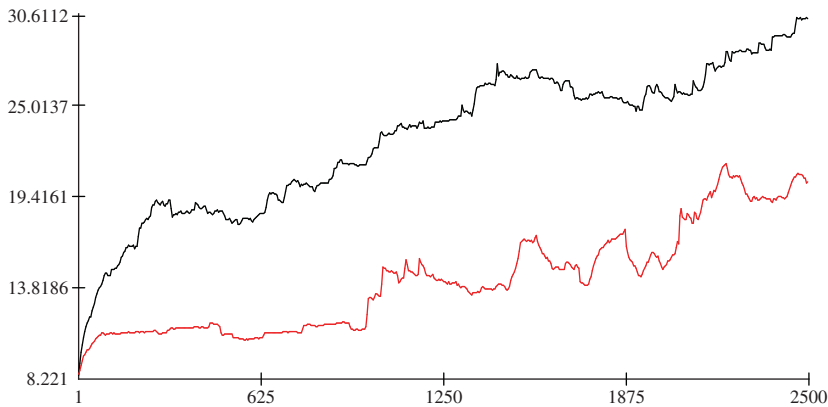


Figure 9. Average product quality, with patents (red) and without patents (black) ($N = 10$, high interdependencies).

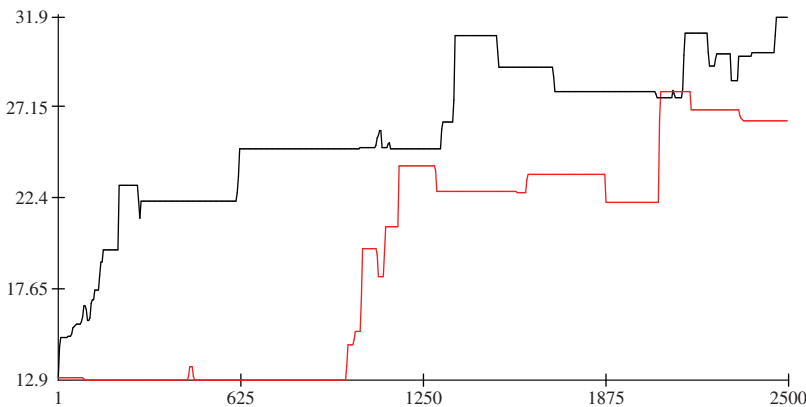


Figure 10. Maximum product quality, with patents (red) and without patents (black) ($N = 10$, high interdependencies).

have to be developed, but they also have to fit together in specific ways. Thus patents have a much stronger blocking effect. In the case of low or no interdependency, it is possible to innovate around a patented product by selecting a path close to the border around its ‘prohibited’ neighbourhood defined by the patent amplitude. Any such path will work and lead to legal innovation. On the contrary, if interdependencies are high, the only innovative paths leading to better products might be instead far away and a vast space around a patented product (much larger than the neighbourhood defined by the patent amplitude) may yield inferior paths. Thus in complex product spaces, the actual, *de facto*, amplitude of a patent is usually much greater than the one set *de jure* by legal norms and practices.

4.2. Coarse versus fine patents

At which level of granularity are firms allowed to patent? That is, can firms patent the whole product, modules thereof or each single component? Coarse patents, granted only on whole products or large modules prevent the marketing of products which are too close (horizontally or vertically) in the whole product (or modules) space, while if each single

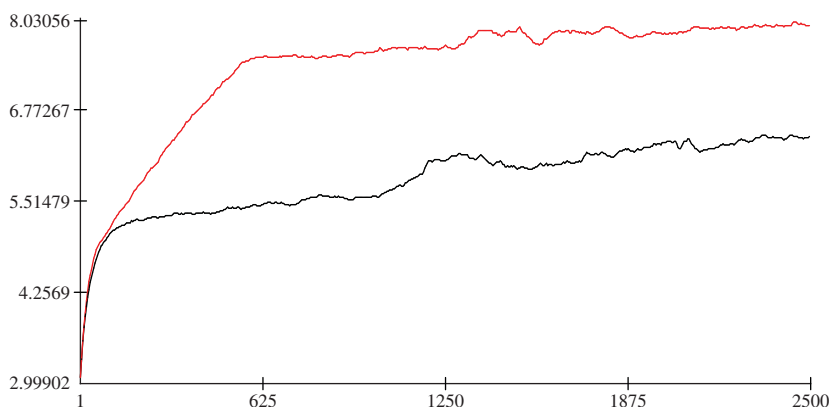


Figure 11. *Consumers' welfare*, with coarse patents (red) and fine patents (black) ($N = 10$, low interdependencies).

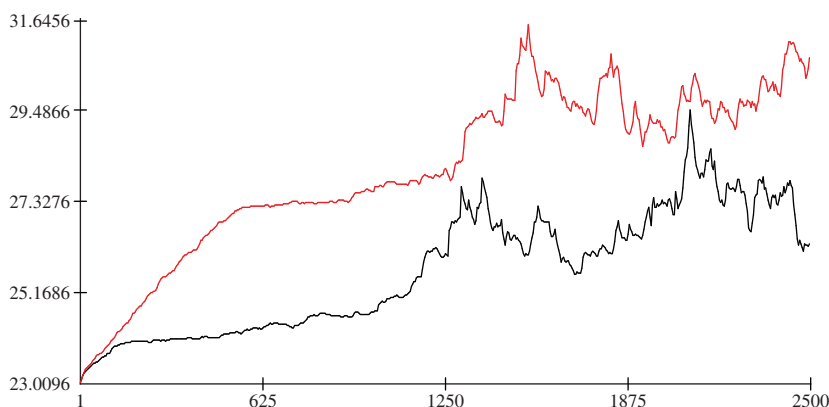


Figure 12. *Average product quality*, with coarse patents (red) and fine patents (black) ($N = 10$, low interdependencies).

component is a patent *per se*, a product containing only one components which is similar enough to a patented one can be prohibited.

This phenomenon, which is similar to the tragedy of the anti-commons and to the patent thicket problem described by the empirical literature, usually connected to the complexity of products, can indeed emerge also in 'simple' highly separable products, as indicated by Figures 11 and 12, that report consumers' welfare and average product quality in an industry characterized by full separability with two different patents regimes, namely one in which only whole products can be patented, and another one in which each single components can be granted a separate patent. We can see that in the latter regime both consumers' welfare and average product quality are inferior in spite of the separability of product components.

5. Conclusions

In this paper, we have approached the study of the effects of patents on the dynamics of an industry and on consumer welfare by means of a model of product innovation where firms search in a complex space of product characteristics and where heterogeneous consumers have different 'ideal' product profiles and look for products with low prices, high quality and

close to their ideal profile. A general conclusion is that product complexity is a key factor determining the long-run efficiency or inefficiency of the patent system. We show that the vicious circle of higher profits, higher R&D expenditures and higher speed of innovation might possibly work and outweigh the loss of welfare due to monopoly when the complexity of the search space is low and therefore there are plenty of possible innovative paths. This of course under the assumption that such a vicious circle correctly describes the real and only appropriation mechanism. An assumption we find largely unjustified as we argue in Dosi, Marengo, and Pasquali (2006). However, when complexity is high, innovative paths are fewer and far between because components have to be combined in specific ways: thus an innovative path may not have any viable alternative in its vicinity and blocking it may considerably slow down further innovation.

These results provide support to perspective which departs from the standard analysis of the costs and benefits of patents grounded into a richer picture of technology and competition. Whenever one abandons standard assumptions equating productive knowledge to information and takes into account its specificities with respect to sectors, technologies and products, one immediately acknowledges that the same patent regime may have very different consequences under diverse knowledge domains. Indeed, one may well conclude that IPRs, being 'universal' rights, are too rough a device to strike the delicate balance between competing interests that is involved in the appropriation of the economic benefits of innovation. Property rights are probably an unfortunate juridical category for the regulation of an issue that should be essentially one of finely tuned industrial policy.

The diversity of technologies and markets should therefore be taken into primary consideration when addressing the problem of incentives to innovation (as such an issue overemphasized in the current literature). A mix of specific policies, rather than universal property rights, could better serve this purpose: diversity of problems requires diversity of solutions.

The broad lesson from the analysis is that if the product space is complex, favouring or blocking innovation in single components through patents has effects which propagate throughout the entire product system in ways that tend to hinder further innovative search. Indeed, as most products in a modern economy are complex in the foregoing definition, the likely implication is that a mechanism of appropriation based upon IPRs is more often likely to be an obstacle, than an incentive, to innovation.

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Notes

1. We owe this comment to an anonymous referee.
2. Testimony of Chuck Fish, Vice President and Chief Patent Counsel Time Warner, in front of the US Senate, Committee on the Judiciary, Subcommittee on intellectual property, 14 June 2005
3. Non-rivalry of technological knowledge and its commonly understood implications have sometimes been questioned. For instance, some scholars claim that non-rivalry is not the proper category (Boldrin and Levine 2002, 2008), and that knowledge and information are rather characterized by (infinite) expansibility (David 1992), that is, they are not jointly consumed like pure public goods, but can indeed be replicated. Replication of information requires some (though possibly very short) time and involves some (though possibly very low) costs and this is enough

- to ensure, they show, that competitive markets price innovation positively and provide incentives to innovators. However, replicability of knowledge entails problems of its own (Winter 2008).
4. Since performance values will be used below in the computation of the utility of consumers, the constant K ensures that the performance value is always positive.
 5. In fact, such an assumption ‘blackboxes’ for the sake of simplicity the distinction between the technical components and the characteristics of the product. Given that our purpose is to address issues of IPRs on components and systems, this simplification is venial.
 6. In the simulations below, we set this ratio equal to $1/4$ of the population of consumers
 7. As a future improvement, we may introduce an adaptive learning procedure on these coefficient of the kind used in (Winter 1984) and based upon a simple ‘satisficing’ heuristic.
 8. See for instance O’Donoghue (1998) for a detailed analysis of the relationships between standard and amplitude of patents and their consequences for sequential innovation.
 9. See again O’Donoghue (1998) for an analysis of the possible consequences of such differences
 10. All simulations are run in the L.S.D. (Laboratory for Simulation Development) platform developed by Marco Valente. The platform may be downloaded along with manuals and tutorials at: <http://www.business.aau.dk/~mv/Lsd/lzd.html>. Programs for the simulations described in this paper may be obtained from the authors upon request.
 11. Notice that in our model, firms are rational enough to exploit the competitive advantage given by product differentiation through innovation and to maximize long-term profits. If we dropped this hypothesis and let also pricing decisions be routinized, conclusions on the efficiency of patents are likely to be different, cf. Winter (1993).

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