THE ECONOMICS OF KNOWLEDGE: A REVIEW OF THE THEORETICAL LITERATURE

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Abstract. A selective review of the existing theoretical literature related to the economics of knowledge with special attention to intellectual property, especially in the form of patents.

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1. Introduction: The Nature of Knowledge[1]

The starting point for any investigation of the economics of knowledge is the observation that knowledge is different in several crucial aspects from 'normal' physical goods. As emphasized by Arrow (1962), and mentioned by many authors before him,[2] knowledge is:

(1) Nonrival (or, at the very least displays significant non-convexities in its production function): in contrast to physical goods, it is, at least approximately[3], costless to reproduce a piece of knowledge once the first 'copy' is made. If one shares a pair of shoes one does not create a new pair – quite the opposite: each party now only has the shoes half the time. However, if one shares a piece of knowledge another gains without any corresponding loss to oneself. As Jefferson eloquently phrased it, over 200 years ago: "He who receives an idea from me, receives instruction himself without lessening mine; as he who lights his taper at mine, receives light without darkening me"[4]
(2) Imperfectly excludable (and, in general, greater excludability comes at the cost of more inefficient use – for example in the form of monopoly pricing). The (partial) nonexcludibility could manifest in many forms, as spillovers to other firms, as the inability of a firm to extract more than the monopoly rent from a given product, or even, to take a case emphasised by Arrow, the fact that the seller of a piece of knowledge faces a unique dilemma in that disclosure may be necessary for the sale but may simultaneously eliminate all demand.[5]

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[1]There have been long-running debates about the distinction between invention and innovation, and between technology and science – as well as whether such distinctions serve any valuable purpose. It is not my object to engage in these discussions here. Instead, I shall assume all innovation is related to the creation of new 'knowledge' – including the knowledge of how to develop associated applications (in this we follow the lead of Foray (2004)).

[2]From the academic literature an early example is the work of Plant (Plant, 1934a,b). As evidenced by the Jefferson quote below, as well as the widespread presence of early modern forms of intellectual property, there has clearly been some awareness of the special nature of knowledge from the very earliest times. However initial thinking on the subject, even among economists was hampered by a lack of clear understanding of the nonrivalrous and nonexcludable nature of knowledge – as well as the interplay between the two (see pp. 17ff of Hadfield (1992)).

[3]We shall return to how accurate this approximation is in some detail below. See, for example, Sections 6 and 6.2.

[4]Jefferson to Isaac McPherson 13 Aug 1813, Jefferson (1905) vol. 13 pp.333–335.

[5]Knowledge, by its nature, tends not to be a homogeneous good and thus a buyer is unlikely to be willing to pay much for a piece of knowledge whose properties are unknown. However, if the seller reveals the knowledge to the buyer in order to demonstrate its value the very act of disclosure serves as to transfer the knowledge and eliminate the seller's market.

Together these lend knowledge the aspect of a 'public good': from the viewpoint of society, once a piece of knowledge is in existence the optimal thing to do is distribute it at marginal cost (which may be zero or very close to zero). At the same time the extreme heterogeneity (and uncertainty) associated with knowledge, as well as its close connection to the production and development of other goods make it hard to adopt a pure 'central-planner' approach of up-front funding (based on taxation) followed by free distribution which is the method adopted for other public goods such as defence – though, of course, much knowledge production is funded in this manner (including this very paper).

The central point to take from this is that due to the special nature of knowledge, its production and distribution can *not* be optimally organized via the free workings of a decentralized market system. Consequently, this is an area of economic analysis which necessarily has a particularly close relation to questions of regulation and policy – be they the optimal form for the intellectual property system to take, or the level of public expenditure on R&D. As Arrow summarized, writing 30 years after his original paper (Arrow, 1993): "knowledge is a hard commodity to appropriate, and it is socially inefficient to appropriate it." This dilemma continues to haunt economists and policymakers today.

2. Early Work and Patent Race Models

Following Arrow, there was scattered early theoretical work looking at various aspects of the 'R&D question', but the absence of game-theoretic tools and the breadth of the field meant that progress was limited and showed little consistency in approach.[6]

However, beginning with a series of papers in the late 1970s and early 1980s (Loury, 1979; Lee and Wilde, 1980; Dasgupta and Stiglitz, 1980a; Reinganum, 1981), there was

[6]Examples of earlier literature include Horowitz (1963), who investigates the incentives for R&D by a single firm in a n-player Cournot model; Scherer (1967), who examines R&D rivalry in a Cournot-style duopoly; Barzel (1968) who raises the possibility that competition induces too early introduction of new technology; (Kamien and Schwartz, 1972a) which investigates in a decision-theoretic framework the optimal R&D program for a firm as a function of market conditions (degree of rivalry etc); Kamien and Schwartz (1972b) which looks at the impact of the degree of rivalry (and imitation) on the innovation level of a 'leader' firm; Kamien and Schwartz (1974), which examines the impact of rivalry on optimal patent design; Kamien and Schwartz (1978) which again looks at the effect of rivalry on the optimal innovation strategy of a given firm (many of these papers by Kamien and Schwartz are collected along with additional material in (Kamien and Schwartz, 1982)).
The main feature of this work compared to that which came later was the absence of any modelling of the strategic interaction between firms. Thus, for example, the long series of papers by Kamien and Schwartz focus only on the optimal behaviour of a single firm as a function of an exogenously given environment – even when rivalry by other firms is an explicit consideration.

sustained attention in the industrial organization literature to developing new 'micro-founded' models of R&D using non-cooperative game-theory techniques. A long line of work, particularly focused on 'patent race' style models, arose whose basic features were:[7]

(1) A focus on the supply-side. These were models of R&D races and the focus was on the suppliers of R&D. The demand-side both in the form of end consumer demand and other firms (licensing) were often black-boxed – in general one would simply assume that a given R&D project would yield income v with social welfare being $w \geq v$.[8]
(2) A known R&D goal (the discovery) shared by all the participants in the race.[9]
(3) A known functional form linking expenditure with discovery.[10] Where the race was dynamic this would entail the use of a memoryless (poisson-style) discovery function (that is the probability of making the discovery only depends on current expenditure and not on past expenditure).[11]
(4) Rational, strategic behaviour on the part of the firms engaged in R&D and innovation.[12]

Even with these simplifications (which were most significant in the area of the demand-side structure and product market competition), there are still multiple factors which generate a divergence between social and private incentives and provide areas for investigation. For example, the difference between social and private returns (problematic

[7]Of course like any generalisation this will not be entirely accurate and we will discuss some of the places where papers differ from this below.

[8]Though e.g. Dasgupta and Stiglitz (1980a,b) both consider explicit models of the product market – perhaps assisted by the fact that these are process innovation models. In particular, Dasgupta and Stiglitz (1980b) develops a fairly detailed two-stage model in which, after choosing cost-reducing R&D expenditure, firms play a standard Cournot game.

[9]That is all firms were attempting to develop the same product or to develop a process innovation for the same product. As such there was little incorporation of the possibility of product differentiation whether of a horizontal or vertical kind (as demonstrated, though not in specific R&D context by Gabszewicz and Thisse (1980); Shaked and Sutton (1983)). However, see Beath, Katsoulacos, and Ulph (1987) for an exception to this tendency.

[10]Scotchmer (2004) for thoughtful discussion of the advantages and disadvantages of 'production-function' style models.

[11]Some work was done on dynamic models that did not assume a memoryless discovery function, for example Fudenberg et al. (1983) and Grossman and Shapiro (1986) as well as the series of papers by Harris and Vickers e.g. Harris and Vickers (1985a,b, 1987). Reinganum (1982) models a dynamic race but assumes a fixed end-point ('doomsday') by which innovation must occur.

[12]An explicit alternative to this approach can be found in the 'non-optimizing', evolutionary, models developed by Nelson and Winter (1982) and subsequent authors.

because of the combination of imperfect appropriability *and* non-convexities), the winner-takes-all aspect of knowledge discovery which results in 'pool' externalities, the divergence between social and private attitudes to risk, the presence of uncertainty and asymmetries in information which give rise to a host of moral hazard and adverse selection problems.

Starting from these considerations a large body of work investigated a variety of questions the most important of which went back to Schumpeter (1947): "What is the market structure which maximises innovation", or alternatively: "Is competition conducive to technical advance?". Specifically:

2.1. **How does the amount of R&D per firm vary with the number of firms?** It decreases according to Loury (1979); Dasgupta and Stiglitz (1980a,b); Delbono and Denicolo (1991);[13] but increases according to Lee and Wilde (1980) (using a slightly modified version of Loury's model) and Reinganum (1982, Prop 6.)[14]; and remains unchanged according to Sah and Stiglitz (1987), who allow firms to choose the number of R&D projects as well as the effort per project (this resembles the situation of a monopolist in many of the other papers).[15]

2.2. **How does total amount of R&D vary with the number of firms?** It increases according to Loury (1979) and Lee and Wilde (1980) but may decrease or increase depending on other factors (such as barriers to entry) according to Dasgupta and Stiglitz (1980b), or even be invariant to market structure according to Sah and Stiglitz (1987).[16]

2.3. **How does this level of R&D relate to optimum.** Are R&D programmes chosen by competitive firms too risky or not risky enough? Not risky enough according to Dasgupta and Stiglitz (1980a), and Judd (1985) (who generalises to a dynamic GE type framework);[17] too risky according to Dasgupta and Maskin (1987, Prop. 5); and either

[13]Delbono and Denicolo (1991) present a model very similar to Dasgupta and Stiglitz (1980b) (who, surprisingly, they do not cite) in which there is process innovation with Cournot competition. As a result more firms have two countervailing effects: under Cournot competition more firms mean lower payoffs to the winner of the R&D race which damps effort, but at the same time one still has the 'pool' externality which drives up effort.

[14]Though as she points out in the following commentary by varying the rewards of imitators versus innovators it is easy to construct examples that go the other way.

[15]Though this invariance result is shown to depend strongly on Sah and Stiglitz's choice of Bertrand competition in the product market – see Farrell, Gilbert, and Katz (2002).

[16]Though see previous footnote.

[17]Later work, such as Cabral (1994), also obtains similar results.

too risky or not risky enough (depending on the skewness of the distribution of returns) according to Bhattacharya and Mookherjee (1986).

Are R&D programmes too correlated? Yes, according to Dasgupta and Maskin (1987). No according to Bhattacharya and Mookherjee (1986).[18] What are optimal subsidies or taxes? Dixit (1988) considers this in detail.

2.4. **How do incentives vary with market structure?** Specifically, what are the relative incentives to undertake R&D of (a) an incumbent monopolist (b) an incumbent monopolist facing new entrants (c) new entrants with no incumbent? Consideration of (a) and (c) was the focus of Arrow (1962), who concluded that due to a 'replacement' effect an incumbent monopolist had less incentives than entrants to do R&D. Dasgupta and Stiglitz (1980a) provide a detailed examination of all of these possibilities and a consideration of (b) versus (c) form part of the next item.

2.5. **Does monopoly persist?** Specifically do incumbents retain their position (persistence of monopoly) or are they 'leap-frogged' by new entrants in a form of Schumpeter's creative destruction? Additionally, does an incumbent (leader) have more or less incentive than an entrant (follower) to spend on R&D?

Gilbert and Newbery (1982) investigate the incentives of a monopolist to engage in 'pre-emptive' patenting (and associated patent shelving) in order to preclude entry. The basic idea[19] is a very simple one: the rents accruing to a monopolist are always at least as large as the total rents available under any other market structure (including duopoly). Thus, all other things being, equal the incentive of a monopolist to remain a monopolist is at least as large than for an entrant to become a duopolist. However, as other authors pointed out, all other things need not be equal. For example, Reinganum (1983), examined a similar situation but in the patent-race framework. In that situation higher spending by the monopolist serves not only to increase the probability that she wins the race (good for the monopolist), but also to hasten the point at which the race ends (bad because she is the current incumbent). As a result, despite the higher rents available to the monopolist

[18]A recent paper, Bulut and Moschini (2006), has shown how the availability of multiple instruments, for example trade secrets in addition to patents, may ameliorate the problem of excessive correlation.
[19]Very similar to that presented in Dasgupta and Stiglitz (1980a, p. 13).

it is possible that the monopolist will spend less than entrants and hence will be less likely to win the race.[20]

Turning to the multi-stage case with certainty in R&D, Fudenberg et al. (1983) and Harris and Vickers (1985a,b), both establish an even more extreme version of this result, in which, whoever has the advantage in the race – be it in terms of valuing the prize more, being better at R&D, or having made greater progress so far, completely dominates (for example, the 'follower' may simply drop out with the 'leader' behaving as if there were no competition).[21] This result arises from the combination of subgame perfection and certainty. Relaxing these assumptions in the second part of their paper, Fudenberg et al. (1983) investigate what occurs when the participants in the race do not know immediately the level of their competitor's effort. They show that this increases the level of R&D both on the part of the 'leader' and the 'follower', furthermore it may allow 'leap-frogging' – a situation in which the 'follower' jumps from behind to the take the lead.

Extending their earlier results to the case of uncertainty in the R&D function, Harris and Vickers (1987) establish that, in general, in a single-stage and multi-stage race (Property 3.1 and Property 4.2) the 'leader' expends more effort than a 'follower'. They also find that in both cases total effort increases as the deficit between the two competitors narrows.

In contrast to this line of papers which implied that incumbency would persist (dominance would increase), Reinganum (1985), which explores a multi-stage patent race model, finds that an incumbent monopolist would spend less than its rivals and that, as a result, there would be a pattern of repeated monopoly with each monopolist being displaced in turn by a new entrant.[22] In a similar vein, Vickers (1986),[23] shows that one can obtain either increasing dominance (one firm extends its technological superiority) or have 'action-reaction' (technological leadership repeatedly changes hands). In his model, which

[20]On a different tack, Salant (1984), in a comment on the Gilbert and Newbery paper, points out that under efficient ('Coasian') bargaining all patents (old and new) will always end up under the control of this firm (precisely because such an outcome maximises rents) and that, as a result, it is not *necessarily* the case that the monopolist has higher incentives to do R&D than an entrant.

[21]Some of the subtleties of the analysis are necessarily lost in a summary such as this. Specifically, Harris and Vickers introduce the concept of 'safety' and 'trigger' zones. In a 'safety' zone a player behaves as if in the absence of competition (and the other player bids 0) while in a 'trigger' zone, whoever's turn it is to move must win immediately (to prevent the other player winning).

[22]Given the different conclusions reached by these different sets of models it is perhaps interesting to note one of the few empirical studies of the topic, that of Lerner (1997), finds that, in the area he studies (the computer disk-drive industry), firms that trail the leader appear to innovate more.

[23]Extended to the case of incremental innovations by Delbono (1989).

features certainty in R&D, which outcome obtains depends on the form of product market competition: 'tough', Bertand-like, leads to increasing dominance while 'soft', Cournot-like, leads to 'action-reaction'.[24]

2.6. **Summary.** As is often the case, it turned out the answer to many of the questions posed was: 'it depends on the model' (or the particular values of parameters in the model).[25] Nevertheless, despite variation in results on many of these issues there was substantial consistency on some basic things. Most importantly, R&D levels could be both too high as well as too low.[26] In particular, competition *in R&D* in a winner-takes-all framework generates increased (even excessive) incentives compared to a monopoly situation.

3. Patent 'Design'

The R&D literature discussed above tended to ignore exactly how the innovator's rents were obtained and how those rents depended on the intellectual property (patent or copyright) regime. After all, there were plenty of other factors to examine.

Nevertheless, the socially optimal design for patents, particularly the examination of the trade-off between the benefits of increased innovative activity and the costs in the form of deadweight losses, had been present from the earliest point[27] and it was soon after the appearance of Arrow's paper that Nordhaus (1969) provided the first attempt formal model of optimal intellectual property policy. Nordhaus, (reinterpreted and expanded upon by (Scherer, 1972)), looked at the basic case of a process innovation that reduced

[24] The question of whether a dynamic oligopoly will produce 'increasing dominance' or 'catch-up' is a general one, not specific to the area of R&D. See, for example, the general model and results of Budd, Harris, and Vickers (1993).

[25] Furthermore, clearly any specific results on items such as taxes and subsidies (e.g. Dixit (1988)) would depend on knowledge of a full array of private as well as public information. In such a situation one must ask why, if the social planner has access to such detailed information, he or she does not simply up-front fund the research and avoid the inevitable dead-weight losses associated with private, patent or secrecy-based, R&D.

[26] The basic reason for this had long been known: on the one hand, firms do not extract the full surplus they generate, while on the other hand, competition encourages the premature introduction of innovations. See for example, Barzel (1968) who noted (p. 348): "It is widely recognized that when innovators are unable to realize the full benefits generated by their innovations the profit motive may not provide an incentive strong for them to innovate at the socially optimal rate. On the other hand, it has *not* been recognized that competition between potential innovators to obtain priority rights (and profits) from innovations can result in premature applications of discoveries. [italics added]"
However, as emphasized by Dasgupta (Dasgupta, 1988), putting this result on a sound theoretical footing was one of the major achievements of the first wave of game-theory, 'patent-race' style, models – along with a include a clearer understanding of the non-additive nature of parallel research (see Dasgupta (1989)).

[27] For example, Plant (1934a,b) clearly considers this, as does Hurt and Schuchman (1966).

the marginal cost of a production process and sought to determine the optimal patent term – the point at which the marginal benefit of increased protection in the form of incentives for a firm to invest to develop a cost saving innovation would exactly equal the extra deadweight losses to society of granting that firm monopoly power for longer. Nordhaus showed, that while (obviously) determining any explicit value for optimal term depended on the parametrisation of the model, one could at least show that optimal term would be finite.[28]

Following the development of the substantial literature on patent races discussed above, the focus widened in several directions. First, there was an examination of the potential for competition in the end product market via imitation. This tied back very directly into the optimal patent literature started by Nordhaus with the added complexity of considering patent breadth as well as patent length. Second, and relatedly there was the question of licensing – compulsory or voluntary.[29]

Once competition in the end product of R&D is to be permitted, due to imitation for example, one needs a model for this competition and how it impacts on the innovator's income (usually one assumes the innovator obtains a patent and so the question is then how its strength vis-a-vis imitators – the breadth of the patent – impacts on the flow of rents per unit period). There are two basic approaches, which we might label the 'reduced form' and the 'microfoundations' (location-model) respectively.

As the names indicates the first approach, taken in e.g. Gilbert and Shapiro (1990); Gallini (1992), involves 'black-boxing' the impact of patent breadth on the patentee's rents in a single functional form, while the second approach, used e.g. in Klemperer (1990); Waterson (1990), involves the provision of an explicit model of the relation between imitators and innovators – usually based on a locational model of some kind (if one is to allow competition in the product space but still retain the concept of excludability one needs a product space which is at least 1-dimensional). These various approaches and assumptions yield a fairly diverse set of results, which are not always consistent.

[28]As emphasized by Horowitz and Lai (1996) this model also implied that the innovation-maximizing patent length exceeded the welfare-maximizing patent length (a point made in relation to copyright by (Landes and Posner, 1989)). Horowitz and Lai study a more general case with multiple patent races and where firms choose both effort and size of innovation. They find that market leader innovates more near patent expiry but that extent innovation is an increasing function of patent term. Overall they establish a similar result to Nordhaus, showing that patent length should be finite and shorter than the level that maximizes the level of innovation. An obvious point perhaps but one often ignored by policymakers.

[29]We shall return to this subject in greater detail in Section 5.

Gilbert and Shapiro (1990), under an assumption that patent breadth is increasingly costly in welfare terms, find that patents with finite width but infinite length will be optimal.[30] Klemperer (1990) by contrast (as Gilbert and Shapiro themselves note), has a more complex situation in which, at least in some circumstances, optimal patents are broad but short. In Klemperer's model all demand is situated at a single point in product space at the same location as the patented product. Breadth is then naturally interpreted as an exclusion radius. Free entry (with zero costs) imply that the patent-holder's price will be then be limited to the cost of 'transport' to the competitive fringe firms on this radius. Thus, in Klemperer's model welfare losses arise not only from the pricing decision but also from travel costs incurred by consumers and the design of the optimal patent must trade-off these two losses.[31] As a result, depending on one's assumption about the distribution of valuations and transport costs, one can have an optimal patent being either long and narrow (Prop. 1 and 2) or, short and wide (Prop. 3 and 4). In the general case the trade-off between width and length will be determined by the relative elasticities of the distribution of values and transport costs.

In a similar vein, Waterson (1990) uses a simple Hotelling line model of product space and considers how the breadth of the patent, interpreted as a simple exclusion zone, impacts (via litigation) on the imitator's behaviour and, thereby, on the innovator's profits and (socially beneficial) product differentiation. Waterson finds that the optimal regime depends on the importance of variety: where it is important narrower patents are desirable, as they allow for entry and thereby increase the number of products on offer, but when variety is less important broad patents, which prevent imitation, are best, as they maximize innovator's rents. Here, in contrast to Klemperer, but in line with standard locational models, all consumers purchase – be it from the innovator or the entrant/imitator, and so the welfare effects arise solely from transport costs and the incentive provided to the innovator.

[30] This has some analogies with the earlier paper of Tandon (1982), who investigates the interaction of compulsory licensing and patent length (just like patent breadth compulsory licensing limits the price a patent holder simultaneously increasing rents and deadweight losses). Similarly to Gilbert and Shapiro (1990), Tandon finds that optimal policy involves patents which are infinitely lived but whose price is limited via the price of the compulsory license.

[31] Optimally one would want all consumers to purchase from the patentee and thereby incur zero travel costs but with unobserved heterogeneity in valuation and/or travel costs the monopolist may set a price above the outside option of some consumers.

Meanwhile, Gallini (1992) emphasises strategic considerations of imitators. If patent length is made longer while breadth is reduced this increases the incentives of imitators to 'invent-around' the patent and thus reduces the patent's actual (as opposed to statutory) life. As such, increasing length and reducing breadth may not, in fact, be optimal. Rather, broadening patent protection but shortening its term, by reducing the incentives of imitators/innovators to invent-around, will provide the optimal way to deliver rents to the patent-holder at least cost to society.[32]

Finally, Denicolo (1996) introduces the possibility that many firms race for a patent and shows how the variety of existing results primarily stem from differing assumptions about the structure of the product market. In particular, he provides simple models in which all combinations of maximum breadth and minimum length, minimum breadth and maximum length and neither maximum nor minimum breadth of length are optimal.

3.1. **Patent Menus.** The 'patent design' literature discussed so far has focused on picking a single optimal value for one or several of the patent parameters. An obvious extension to this approach as been to allow a *menu* of possible values for, say, patent length combined with a set of associated fees – in fact most patent offices already had a system like this in which fees were charge annually for the renewal of the patent (though their motivation for this approach rested on simple cost sharing rather than any consideration of mechanism design).[33]

Thus, for example, Scotchmer (1999); Cornelli and Schankerman (1999), examine the case where a menu of lengths and fees are offered and show that a menu can be welfare improving. Cornelli and Schankerman (1999) show, furthermore, that a renewal system (as opposed to a simple fee) offers additional advantages if there is ex ante uncertainty about the value of a patent. Hopenhayn and Mitchell (2001) extend the menu approach to the case where firms can also choose the breadth of their patent and show that by trading off breadth and length one may not require fees at all (though, compared to length, it is harder to see how, in practice, a policy-maker is to offer a variety of breadths).

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[32]Note, that 'inventing-around' will result in just the kind of wasteful duplication of effort that underlie the 'pool' externalities of the standard patent race literature.

[33]Note also, that for some time before this theoretical attention several empirical papers, most notably Pakes (1986); Schankerman and Pakes (1986); Lanjouw (1998); Schankerman (1998), had used patent renewal data to estimate the distribution of patent values.

3.2. **Novelty and Non-Obviousness.** There are usually considered to be three requirements for a discovery to be patentable: it must not fall within an excluded subject area (for example, up until very recently most jurisdictions excluded business methods from patentability); it must be novel; and it must be non-obvious (have an inventive step).[34] Thus various authors have looked at varying some of these other characteristics, in particular novelty and the non-obviousness requirement (the size of the inventive step). From an economist's perspective, particularly when developing a model, it is not clear that novelty adds anything beyond non-obviousness – anything which is non-obvious represents an advance beyond what is currently known and therefore must, a fortiori, be novel.[35] Furthermore, novelty is a purely binary concept: either an invention is novel or it is not and it would seem odd indeed to have a patent system which allowed the (re-)patenting of existing work. Thus, our focus reduces to that of considering the non-obviousness/inventive step requirement. Given that the concept of an inventive step implies some form of advancing (cumulative) line of innovation, we shall defer the question of its optimal design to the next section, which deals exclusively with that subject.

4. Cumulative Innovation

The idea of multi-stage patent races was present in some of the early work[36] but the focus was on the differing behaviour of participants over the entire race. Furthermore most of these approaches, at least implicitly, assumed technological independence between stages (and between firms) and focused instead on strategic dependence between stages (the same firms took part in the different stages). For example, as discussed above, a long line of models considered how an incumbent monopolist competed against new entrants to develop a new drastic (or non-drastic) process innovation. Even in those models which explicitly incorporated multiple stages there was little sense that a new innovation 'built-upon' the old – there was, for example, no requirement that a new innovation be sufficiently

[34]Some jurisdictions, such as the US, also include a requirement – rather similar to the first – that the invention must be susceptible of industrial application.
[35]Even an article such as Scotchmer and Green (1990) which contains 'Novelty' in its title is, in actual fact, an article about the size of the inventive step.
[36]Many of the models considered cases in which new entrants competed with an incumbent to develop a new innovation (see above section for references), and many models, e.g. Reinganum (1985); Harris and Vickers (1987); Vickers (1986); Delbono (1989), had explicitly modelled multi-stage innovation.

'big' in order to qualify for protection, or for a new innovator to obtain a license from the owner of the previous innovation.

By contrast, the cumulative innovation literature discussed here emphasized the technological dependency between stages – while allowing greater strategic independence (the set of firms participating in different stages were often completely unrelated). In a manner similar to the quality-ladder literature innovations were considered as advancing along some set of quality dimensions (usually one for simplicity). Patent breadth could then be (re-)interpreted[37] as distance along this line, and, depending upon the structure and strength of intellectual property rights, new innovators might infringe existing rights and therefore require a license to produce. Furthermore, new externalities (or old ones in new forms) arise: are early innovators, who develop the base upon which future developments will build, adequately compensated for the potential they create (its 'option' value);[38] will existing innovators inefficiently exclude those who might extend their work?

It is in this sense that cumulative innovation 'ups the stakes': in traditional models of optimal patenting the only limit on infinite patent length was monopoly cost. These costs are generally thought to be relatively small.[39] Given this, and that private firms – even with intellectual property rights – are unlikely to extract anything close to the total social surplus of the innovations they produce, this would imply that patents should be as long as possible (and fairly wide too). But once we have cumulative innovation we need to consider the impact of higher 'prices' (in the form of licensing and transaction costs) on future innovators. Furthermore, when a given innovation does not occur society loses the entire social surplus – which may be very large.[40] Thus, with cumulative innovation, because intellectual property may result in lost follow-on innovation as well as traditional deadweight losses, the costs of too much intellectual property may be substantially higher than in a single innovation context. Conversely, the costs of too little intellectual property

[37]One could see the previous literature on patent breadth, discussed above, as focused on horizontal differentiation (being different), while cumulative innovation dealt with vertical differentiation (being better). Of course, the distinction between better and different in many cases is a fine one.

[38]This question clearly has important analogies with the literature on general spillovers, see Spence (1984), D'Aspremont and Jacquemin (1988) etc.

[39]Initial work on this by Harberger (1954) (extended by Schwartzman (1960)), found relatively small welfare losses from monopoly. That said, recent work on the effect of patents in the Indian pharmaceutical industry (Chaudhuri, Goldberg, and Jia, 2006), found very large effects, with consumer welfare losses over ten times producer gains (though note that in their paper losses arise not just from higher prices but also from a loss of choice).

[40]An analogous point is made in the context of trade barriers by Romer (1994).

may also be much larger: when a given (first-stage) innovation fails to be made because expected rents are too low, society loses not just the value of that innovation but the value of all innovations that would have built upon it.

In terms of the literature, a general awareness of cumulativeness of knowledge has been present from a very early point – it is after all, an omnipresent phenomenon in most areas of human enquiry. However there was little formal modelling prior to the early 1990s.[41]

Initial surveys include Scotchmer (1991), who focused on the first issue mentioned above (that early innovators may not be adequately compensated for the 'option-value' of their innovation), and Merges and Nelson (1990) who provide a multitude of examples that demonstrate in relation to the second issue ('hold-up' or exclusion of follow-on innovators). However the first formal models was provided by the paper of Chang (1995) and Green and Scotchmer (1995). Chang examines the situation where a new innovation builds upon an old and the stand-alone values of the two innovations differs (the stand-alone value is that which would obtain in the absence of infringement and associated licensing). He shows that optimal breadth[42] is not a monotonic function of the relative values of the two-products. Courts should grant broad protection both to first-stage products that are very valuable relative to the improvements and to those that have very little (stand-alone) value relative to improvements.

Green and Scotchmer, focus on the possibility of ex ante licensing, and how the interrelation of ex ante vs. ex post licensing payoffs affect the incentives of the innovators at the two stages. In their model, in contrast to Chang, first-stage firms have perfect information about second-stage firms' values and costs. This combined with efficient bargaining eliminate any possibility of 'hold-up' (the situation where second-stage firms do not invest either because of anticipated or actual hold-up of their investment at the licensing stage). As a result Green and Scotchmer tend to find that very broad (even infinite) protection is optimal.[43]

[41]There are of course exceptions: for example the 'prospect theory' of Kitch (1977) implicitly assumes some form of cumulative innovations (otherwise there is nothing for the initial patent-holder to coordinate).

[42]Breadth here is interpreted in terms of the probability that the second-stage product infringes on the first firm's patent and vice-versa. Thus a large breadth means the second-stage product is likely to infringe while a narrow breadth means it is likely not to.

[43]Though, interestingly and rather counter-intuitively, with uncertainty (but symmetric information) about second-stage costs a shorter (finite) breadth may be optimal. The reason being that a reduction in breadth increases the ex post payoff of the second-stage firm. In so doing it reduces the ability of the second-stage

Building on this framework Scotchmer (1996) points out that if second-stage innovations are patentable, even with multiple competing second-stage firms, a first-stage innovator will be unable to extract the full 'option-value' of the innovation. Bearing this in mind, she asks whether in some cases it might not make sense to increase the bargaining power of first-stage firms even further by making second-stage innovations unpatentable (in which case, under perfect information, a first-stage firm can extract all surplus).[44]

Denicolo (2000) extends the model of Green and Scotchmer to incorporate patent races at the two innovation stages (though he simultaneously simplifies the licensing aspect). Here stronger intellectual property (greater breadth) in the form of second-stage products being infringing increase the rate of first-stage innovation but retards the rate of second-stage innovation (compared to the non-infringing case). Welfare (and policy considerations) are complicated by the fact that in addition to this trade-off one must also incorporate the effect of 'excessive' incentives generated by racing as well as the opposing effect generated by the gap between the private and social value of innovations. Denicolo finds that it will generally be better to make second-stage products patentable (in contrast to (Scotchmer, 1996)) and that in some cases breadth should be wide (second-stage products infringe) but in others the breadth should be narrow (second-stage products do not infringe).

Matutes, Regibeau, and Rockett (1996), introduce yet another, subtly different, version of breadth. In their model there is a single 'basic' innovation of little value by itself but with many valuable applications (furthermore the creator of this basic innovation may conceal its existence for some period while developing applications). 'Breadth' is then the number of these applications that are 'reserved' for the owner of the basic patent. They then contrast the breadth of protection (how many applications are 'reserved' in perpetuity) versus the length of protection (protect all applications for some fixed period T). They find a general preference for the breadth rather than length approach, primarily because of its effect on eliciting early disclosure.[45]

firm to threaten to not invest (because of the hold-up risk) and therefore shifts bargaining from the ex ante to the ex post stage. This benefits first-stage firms and the overall result is to increase innovation.

[44]Both in assumptions and conclusions this result has some analogies with Kitch (1977).

[45]Referring back to the basic 'breadth' literature discussed in section 3 this can be seen as similar to 'finite-breadth/infinite-length' type regime recommended by e.g. Gilbert and Shapiro (1990).

Meanwhile O'Donoghue, Scotchmer, and Thisse (1998) present a very rich model which incorporates: (a) patent-race style (poisson-process) arrival of ideas in a cumulative chain (so each idea represents an improvement on the current innovation); (b) a distribution of idea values (so not all ideas become innovations); and (c) a homogeneous or heterogeneous set of consumers.[46] By having an infinite sequence of ideas (and related innovations) the authors are able to differentiate between leading breadth (how new a new innovation must be to be non-infringing) and lagging breadth (how far behind the current state of the art an imitator must be to be non-infringing). They consider various possible policies, specifically full lagging breadth only, infinite leading breadth plus finite patent life, finite leading breadth plus infinite patent life (note that in this context a patent's life may terminate either when the patent expires or when it is superseded by a new non-infringing innovation and thus both these cases correspond to finite *effective* patent life). They show that in the simple (non-oligopoly) model lagging breadth alone will not provide sufficient incentives for R&D[47] and that either of the alternative policies may provide a remedy (though with subtly different effects on welfare).

Returning to a simpler Green and Scotchmer style model, Bessen (2004), focuses on ex ante licensing combined with asymmetric information about the values/costs of second-stage innovations (which are not known to first-stage firms). As a result hold-up can occur: first-stage firms will set the royalty rate to maximize expected royalty income and this rate will be above the level some second-stage firms are willing to pay. As a result there will be a trade-off between transferring rents to first-stage firms (which encourages innovation at that stage) and the hold-up of second-stage firms (which reduces the level of second-stage innovation). Looking at the optimal policy in the form of an exogenously (society-determined) ex-post royalty rate, Bessen shows that the optimal level of such a royalty is below that chosen ex-ante by first-stage firms. As a result in his model all licensing occurs ex post at the societally-determined level – a finding he interprets as fitting with the empirical work of Anand and Khanna (2000) on the structure of licensing contracts.

[46]This second case permits oligopolistic competition in a vertically differentiated market a la Gabszewicz and Thisse (1980) and Shaked and Sutton (1983).

[47]Though, perhaps rather surprisingly, in the richer oligopoly model with heterogeneous consumers these need not be the case. Here because firms enjoys rents both as leaders and followers, lagging breadth alone may be sufficient to elicit efficient investment if new 'ideas' are 'infrequent' (see Prop. 5 p. 18).

In recent, as yet unpublished work (Bessen and Maskin, 2006), Bessen along with co-author Eric Maskin, extends this model to case where there is a sequence of innovations. At each stage there are (the same) two firms, each of which may choose to participate or not in researching the current innovation. The next innovation stage is reached if, and only if, research at the current stage is successful and success is an increasing function of the number of participating firms and the authors consider two possible regimes: one in which there are patents and one in which there are not. With patents the patent-holder can extract the full value of the innovation and, because subsequent innovation are assumed to infringe, allow the patent-holder to extract a license fee from the follow-on innovator. Without patents both the winner and a loser of a given stage receive a fraction s of the innovation value and the winner has no rights over subsequent stages. Finally, and importantly, just as in the original model there is asymmetric information about costs: firms come in two cost-types and the cost-type is only known to the firm and not its competitor.

As a result of this asymmetry of information, when patents exist, a patent-holder may set a royalty-rate which is too high for a high-cost firm to participate. As a result that firm will be excluded from participation in future innovation stages and the value of this participation is thus lost. As a result there are costs as well as benefits to having patents and as Bessen and Maskin show (Proposition 7, p. 29) in some circumstances (a sufficiently dense tail to the distribution of innovation values and a low enough probability of a low cost innovation) the costs may outweigh the benefits and a regime without patents will yield more innovation (and social value).

4.1. **Inventive Step.** As already discussed, cumulative innovation models were often used to evaluate policy, particularly in relation to the vertical breadth of protection. Another natural, but more specific, application was in the evaluation of the inventive step requirement (see Section 3.2 above). An early paper was that of Scotchmer and Green (1990) which though formulated in terms of novelty was in essence about the size of an inventive step. Contrasting a strong with a weak novelty requirement the paper mainly focused on the strategic impact of disclosure on discouraging firms from patenting small improvements even when this was possible under a weak novelty scenario.

Looking more directly at the inventive step issue, van Dijk (1996) investigates a duopoly model of vertical (quality) product differentiation in which an 'imitative' firm can choose the size of its improvement to the original innovator's product and the choice is constrained by the size of the inventive step. Van Dijk shows that a low inventive step makes no difference to the choice of an imitator, a medium inventive step actually harms the innovator by 'committing' the imitator to a higher level of effort and a high inventive step benefits the innovator by blockading the market completely and leaving them in a monopoly position.

Turning to an infinite sequence of innovations, O'Donoghue (1998), develops a 'quality-ladder' model with an infinite sequence of patent races in which firms may choose both their effort and the size of the targeted innovation.[48]. The technological leader alone makes a profit and this profit is a function of the difference between the quality of her innovation and the next best available. In addition to leading and lagging breadth O'Donoghue considers the size of the inventive step and shows that a patentability requirement (a minimum inventive step size) can stimulate innovation because it extends the effective life.[49]

Hunt (2004), develops a similar model though he endogenizes entry (using a fixed entry cost) and makes the size of a given innovation exogenous. Hunt's central result is that the rate of innovation is an non-monotonic function of the inventive step with a unique inventive step size that maximizes the rate of innovation. This is due to the interaction of two competing forces: on the one hand a larger inventive step makes it more likely that a firm's research efforts will yield no profits (because the invention will not be patentable) but on the other hand it extends the period of incumbency for a firm that does obtain a patentable invention. For similar reasons, Hunt also finds that in his model an industry with faster technological progress should have a higher inventive step.

5. Licensing

The question of licensing is an important one – and of much more general concern than simply in its relation to cumulative innovation. Questions that arise include why and

[48]This approach is very similar to O'Donoghue, Scotchmer, and Thisse (1998) (see above) and builds upon the approach developed in the endogenous growth literature by Aghion and Howitt (1992); Grossman and Helpman (1991a).

[49]Though there are some subtleties: for example, in the case of a nonlinear profit function a minimum inventive step, while increasing the efforts of followers, may have an ambiguous effect on the leader's incentives (see Proposition 4, p. 670).

when firms will license, the structure of licensing contracts, and the effect of licensing on R&D incentives and welfare. Prominent examples of work on these topics is provided by Gallini (1984); Gallini and Winter (1985); Katz and Shapiro (1985a); Kamien and Tauman (1986); Gallini and Wright (1990); Anton and Yao (1994).[50]

Gallini (1984) emphasizes the strategic incentives for an incumbent to license its technology to an entrant to reduce the incentives for the entrant to do R&D;[51]. In a different vein, Gallini and Winter (1985), investigate incentives to license in a duopoly and its effect on R&D incentives. In their model firms always license but the availability of licensing can have differential effects on R&D effort depending on how competitive is the initial position of the two firms (measured in terms of the closeness of their production techniques). Licensing encourages R&D when firms are initially close but discourages it when they are asymmetric.[52] The authors also make the point that, where it is possible to keep information secret, patents may be seen as facilitating (rather than reducing) information flow since providing 'property-rights style' protection enables licensing. This argument is usually known under the title of the 'contract theory of patents' and has continued to receive attention in the literature.[53]

Meanwhile, Katz and Shapiro (1985b), investigate all of the main licensing questions using a three stage game where R&D is followed by licensing and then competition in the output market a la Cournot. In their model not all innovations are licensed, with low value innovations more likely to be licensed than high value ones. Regarding both

[50]Closely related to the issue of licensing is the possibility of cooperation in R&D. In this literature spillovers play a prominent role (with cooperation being one means of internalising them). There is now a large literature, which we are not able cover in detail here – for examples see, Katz (1986); D'Aspremont and Jacquemin (1988); Katz and Ordover (1990); Suzumura (1992); Simpson and Vonortas (1994); Ziss (1994); Leahy and Neary (1997); Katsoulacos and Ulph (1998); Goyal and Moraga-Gonzalez (2001).

[51]A similar point is considered by Rockett (1990) (and following her (Eswaran, 1994)), who investigates selective licensing by incumbents as a strategic tool for 'selecting the competition' so as to prolong their dominance post patent expiry.

[52]This result has interesting analogies with the recent paper of Cabral and Polak (2007) who examine the relationship between dominance, imitation and innovation. They find that dominance is bad for R&D when intellectual property rights are weak but good when they are strong.

[53]For a recent example see Denicolo and Franzoni (2003). However, it should be noted that intellectual property rights are not essential to licensing knowledge even in the presence of the sorts of informational asymmetries emphasized by Arrow (1962) – see, for example, Anton and Yao (1994, 2002), who explore how an innovator might be able to extract rents under licensing even in the absence of intellectual property protection.

R&D incentives and welfare the effect of licensing is ambiguous with a negative or positive impact possible depending on parameters.[54]

Kamien and Tauman (1986), look at the structure of licensing contracts where competition takes the Stackelberg form (with the innovator the leader). Non-drastic innovations are licensed to all competitors using a fixed fee (not a per-unit royalty) while drastic innovations are licensed to a single firm. Similar questions are addressed by Gallini and Wright (1990), who investigate the structure of licensing contracts (linear vs. non-linear, exclusive vs. non-exclusive) in the presence of asymmetric information and the possibility of imitation. They show that high and low value innovations will be licensed differently with low value innovations licensed exclusively for a fixed fee but high value innovations will usually use an output-based format (though possibly with a fixed fee).

6. Imitation[55]

The empirical literature on innovation and intellectual property, from an early stage, indicated that an intellectual property right, such as a patent, provided a very imperfect monopoly, with competing firms often able to 'imitate' a given innovation well before the formal expiry of the patent.[56] The same literature also tended to show that 'imitation' was a non-trivial exercise which even in the absence of a patent might require substantial time and effort.[57] This stood in contrast to much of the early theoretical literature, which as Levin (1986) emphasized, tended to assume that patents provided perfect excludability (and even in some cases perfect appropriability).

There were of course exceptions. Reinganum (1982),[58] incorporated the possibility of imitation (though in her model imitation simply yields a lower return to innovation – it is still costless and instantaneous). Horstmann, MacDonald, and Slivinski (1985), develop

[54]The same authors produced a whole series of further papers on this topic, see for example Katz and Shapiro (1986) which examines the strategy of a research lab licensing to firms who are product market competitors, and Katz and Shapiro (1987) which examines the innovation effort in a duopoly when ex-post dissemination either via licensing or imitation is possible.

[55]Closely related to the question of imitation is that of the diffusion of a given innovation. There is now a large literature on this topic which we will cover in detail in this review. As a starting point the reader is directed to Griliches (1957); Reinganum (1981); Jovanovic (1982); Jovanovic and MacDonald (1994); Gort and Klepper (1982); Klepper and Simons (2000).

[56]See for example Mansfield (1961); Taylor and Silberston (1973); Mansfield, Schwartz, and Wagner (1981); Mansfield (1985) and Levin et al. (1987).

[57]A point made particularly strongly by Dosi (1988).

[58]An even earlier example, that builds on the analysis of Scherer (1967) was Baldwin and Childs (1969). Another early work that included imitation to some extent was Futia (1980), who has an exogenous level of entry and imitation in his model of Schumpeterian competition.

a model that allows imitation even where patents are present in an effort to explain why firms only patent a proportion of their innovations. Here a patent may signal to a competitor that opportunities are 'good' and hence encourage imitation (without the signal the competitor might simply exit the market leaving the innovator as the monopolist). On a different tack, Benoit (1985), has a duopoly model in which the innovation is not patentable and imitation by the non-innovator is possible. Here imitation is as costly as innovation but there is uncertainty about the value of an innovation which is only resolved once it is discovered. As a result, imitation may drive down innovator rents: the innovator still loses on 'bad' innovations but now has its profits reduced on good ones; and, as a result, the level of innovation may be a non-monotonic function of innovation cost with a firm more willing to undertake higher cost innovations.[59]

Following this early work came the literature on patent breadth which we have already discussed above. Here, the relationship of patent scope had a direct impact on the development of imitative products. This was a substantial improvement in realism – there was now an explicit product space in which imitation did not have to be perfectly duplicative – but there was a tendency to still see patents as perfectly exclusionary within their scope and for imitation to be costless.[60] One paper that does allow for both costly imitation and product differentiation, though restricted by an assumption of exogenous participation (there are just two firms), is Harter (1994). Building on the model of R&D in a Hotelling model of product differentiation developed in Harter (1993), he allows patenting by the innovator and for imitation of the innovation (the effect of a patent here is two-fold: it makes imitation cheaper but the imitator must locate her product outside of the exclusion zone set by the patent).[61]

6.1. **Endogenous Growth Style Models.** A rather different strand of literature on the topic is that coming from quality-ladder style models of endogenous growth. These

[59]Taken to an extreme, if imitation is sufficiently cheap and effective then firms will prefer to imitate rather than innovate and there will be a 'waiting-game' rather than a patent race – see Katz and Shapiro (1987); Dasgupta (1988) for early discussion and Choi (1998) who as part of a wider paper on patent-litigation, patent strength and imitation investigates waiting-game style behaviour in *imitation*.

[60]Such generalisations are never entirely accurate. Gallini (1992) has costly imitation though her model does not feature product differentiation.

[61]An example of an alternative approach where imitation costs are non-zero is that of Pepall and Richards (1994). Their model features quality choice by the innovator, uncertainty about demand, perfect but costly imitation and Stackelberg quantity competition in the final product market. They find that imitation may lead to welfare losses due to inefficiently low choice of product quality by the innovator.

naturally tend to have a strong connection to the work on cumulative innovation already discussed.[62] Early work incorporating imitation in a dynamic general-equilibrium framework included that of Segerstrom (1991); Grossman and Helpman (1991b) and Helpman (1993).

Segerstrom (1991) and Grossman and Helpman (1991b) build similar models based on the framework developed in Grossman and Helpman (1991a) but allow firms to engage in costly imitation as well as innovation. Grossman and Helpman analyze a model with two regions: a 'North' and a 'South'. Innovation only takes place in the North and imitation only takes place in the South and in both cases follows a classic patent race form. Due to factor price differences if firms from both regions simultaneously have access to the same product quality the Southern firm produces (Bertrand competition with cost differences). By contrast, Segerstrom has a single region and a firm in a given industry may engage in both imitation and innovation that follow a patent-race format with imitation being cheaper than innovation, and firms with the same technology play an oligopoly game which allows for collusion (collusion does in fact occur in equilibrium yielding non-zero profits for firms even when there are multiple participants). As a result both imitation and innovation occur (though not at all stages) and imitation reduces incentives to innovate.[63]

Neither of these models explicitly considered the impact of intellectual property rights. This is something considered by Helpman (1993). However, the paper's focus is a rather 'macro' one, aimed at evaluating the different channels by which an increase in the strength of intellectual property rights impacts on welfare – whether via terms of trade, production composition, available products, intertemporal allocation of consumption, etc. As a result, the model of innovation and imitation is highly simplified.[64]

More sophisticated, recent, work that incorporates both competition and some measure of intellectual property protection is that of Aghion, Harris, Howitt, and Vickers (2001).

[62] Indeed many of those models, particularly those with multiple stages, incorporate imitation. However they usually do so in a rather basic form – imitation is instantaneous outside of the scope of the patent and impossible within it.

[63] In a subsequent paper Segerstrom with co-author Davidson (Davidson and Segerstrom, 1998), investigate the impact of R&D subsidies on growth, in a similar endogenous-growth style model that again includes imitation as well as innovation.

[64] Helpman uses a North/South model similar to that of Krugman (1979) and imitation simply occurs at some exogenous rate determined by the intellectual property policy parameter. Neither innovation nor imitation require resources. This is obviously a substantial simplification (as Helpman acknowledges see fn. 5 p. 1250) but is in accord with the focus of the analysis.

Their model modifies the standard quality-ladder by turning each industry into a duopoly with differentiated products (so firms compete via price competition but not in a pure Bertrand form). Firms innovate to reduce costs and the laggard engages in imitation. Both processes take patent-race form but imitation occurs more quickly that innovation. Intellectual property rights are not explicitly present but there is general 'substitutability' parameter α which can be seen as proxying the absence of barriers (such as intellectual property) to direct entry into a rival firm's market.[65]

To conclude, all of these endogenous-growth style models offer a rich approach to considering imitation rather different from that found in a 'normal' IO literature. However, partially as a consequence of their complexity in other areas, they tend to be rather restrictive in two important ways. First, one cannot use them to explore inter-industry heterogeneity in innovation and imitation behaviour. Second, and most importantly, in contrast to the 'cumulative innovation' literature there is no modelling of micro modelling of the licensing process (an innovator or imitator never has to negotiate with existing producers).

6.2. **Capital-Style Models of Free Replication of Knowledge.** The effect of removing the assumption that imitation is instantaneous has been addressed, albeit using a rather more macroeconomic approach, with very interesting results in the recent work of Boldrin and Levine (2003, 2005) and Quah (2002) (hereafter BLQ). In these models 'ideas' are treated like capital in a standard macroeconomic general equilibrium model, and, once created, have a standard neoclassical production function determining the rate at which new copies can be made. The main difference between 'ideas' and capital is that there is a one-off charge to create the first 'copy' of an 'idea' (the fixed cost of the innovator). In equilibrium, if the 'idea' is to be instantiated, this fixed cost must be less than the first period price (the income received by the innovator). It is shown (the most thorough treatment is by Quah) that, in the absence of intellectual property rights (i.e. under conditions of free competition): a) initial prices are bounded away from zero and thus the level of innovation is non-zero b) (Quah Thm 4.9) that there exists a non-trivial

[65] Aghion, along with co-authors, has done a substantial amount of subsequent work along similar lines. For example, Aghion, Bloom, Blundell, Griffith, and Howitt (2005) looks at how incorporating the level of product market competition into a Schumpeterian model can help explain the empirical finding of the 'inverted-U' shape relationship between innovation and competition observed empirically. However these papers tend to have a highly simplified model of imitation as their primary focus is elsewhere.

competitive innovation equilibrium c) (Quah 4.10 and Fig. 1) this equilibrium will (probably) not be socially efficient (i.e. there are conditions under which it will be efficient but these conditions are rather restrictive) d) changing the rate of reproducibility, that is the rate at which one can copy, may increase the first period price and therefore the revenue to the creator of the first copy.

BLQ are making an important point in highlighting the restrictive nature of a pure nonrivalry assumption. However, there are, in turn, several problems with their alternative. Most fundamentally, while it is undoubtedly true that new 'ideas' must be embodied, be it in goods, services or human capital in order to be useful this does not necessarily make the underlying 'ideas' nonrival. Suppose, for example (following Romer (1990)), that we have a new design for a hard disk drive which halves the per unit storage cost. Now, while it is clear that only the disk drives themselves have value to end consumers, nevertheless if the design can be copied at less than the cost of its original development we still have all the traditional problems: competition will drive price to marginal cost of production plus the cost of copying the new design and, assuming the cost of copying is less than the cost of the original development, the creator of the original design will make a loss.

BLQ's model avoids this outcome by equating idea production with capital production in standard neoclassical macroeconomic models. Just as new capital is produced from old in those models so new copies of an idea are made from old. But this analogy is misleading, since it papers over the fundamental distinction between capital in a neoclassical growth model and ideas in an innovation model: while reproduction of capital can be viewed as a homogeneous process (though even this might be dubious) reproduction of ideas is not. Once an imitator has made the initial copy of an idea, 'normal' production, using capital and labour, kicks in and there is no constant returns to scale in the idea. But if that is so, other than the delay (which *is* important and is the major insight of these models), we are back to our original situation where the original innovator will be out of pocket.

In explicit production function terms: if any copy can be used as a basis for reproduction – as in BLQ, but that, unlike BLQ, once one copy of an 'idea' is made you can make additional ones using capital following a CRS production function $f(n, k)$ where n is the number of ideas (think of reproducing CDs be it as stamped plastic in a factory or as bits on a computer) then: $f(0, k) = 0, f(n, k) = f(1, k)$ for all $n \neq 0$ and $f(1, k) = \alpha k$.

Thus, there is nonconvexity with respect to ideas. Under competition this implies that any second period price must be α and profits are zero. But then no-one would be willing to pay more than 0 for a copy of the idea and the originator cannot cover development costs.

Nonetheless BLQ do perform a valuable service in focusing attention on the fact that reproduction is not instantaneous. This ties in closely with the empirical fact of lead-time advantages. However to understand this fully we must introduce a clear distinction between imitation and reproduction. Imitation is the making of a first copy – a template – by a new producer who is not the originator. Once a producer has this first copy it may engage in reproduction: the making copies of its own copy in a standard manner.

Armed with this definition traditional nonrivalry can now be interpreted as the assumption that imitation is the same as reproduction. Conversely, with this definition, it is easy to see the similarities of imitation to original innovation:

(1) A fixed cost of creating a first 'copy': imitators have 'development' costs just like innovators.
(2) Producing a 'copy' takes time: imitation just like innovation is not instantaneous.

7. Open[66] Approaches to Knowledge Production[67]

Recent years have seen a variety of areas in which open approaches to knowledge production feature prominently. For example, in the software industry we have the phenomenon of open source software[68] while in the area of online content we have sites such as Wikipedia.[69] Such developments stimulate one to ask: how well can an open approach

[66]An 'open' approach to knowledge production is one where the resulting knowledge is 'open', that is, it can be freely used, redistributed and reused. The word 'freely' must be loosely interpreted – for example the requirement of attribution or even that derivative works be re-shared, does not render a work unfree. However it does exclude the requirement of payment, or the imposition or restrictions on the type of use (such as limiting the use to research or non-commercial activities). Furthermore, since, without access, a piece of knowledge cannot be used it also excludes the use of secrecy – 'open' knowledge must be publicly available.

[67]The discussion in this section can usefully be supplemented by the more extensive survey in Pollock (2006a).

[68]The literature on open-source is growing rapidly. For an introduction and overview see Lerner and Tirole (2002, 2005); Maurer and Scotchmer (2006). Examples of early work include Benkler (2002); Von Hippel (2002); Casadesus-Masanell and Ghemawat (2003); Lakhani and von Hippel (2003); Gaudeul (2004); Bonaccorsi and Rossi (2004); Bessen (2006).

[69]Of course, open approaches are by no means new: consider the two century old example of John Rennie, one of the most famous engineers of the industrial revolution. In 1789 he worked on the Albion Mills for Watt and Boulton. To Watt's horror, upon completion, Rennie, rather than patenting his new design, was eager to demonstrate it to others. "[F]ar from ruining him [Rennie] as Watt predicted, [this] established

to knowledge production do? Are there models in which an open approach to knowledge production would be optimal. In particular, how (and why) could an open approach to the production of knowledge goods be superior, in terms of innovative output, to one based on exclusive rights? It is important to note here that we are focused on the rate of innovation and not the level of welfare. After all it is well-accepted that being more 'open' (having weaker intellectual property rights) can improve welfare by improving access.[70] But this is certainly not the case in relation to innovation. In fact most of the literature, implicitly or explicitly, would support the following propositions:

Proposition 1. *The level of R&D (and hence the rate of innovation) is increasing in the payoff from successful R&D (e.g. the level of reward from winning a patent race).*

Proposition 2. *Strengthening intellectual property rights such as patents increase the payoff to successful R&D (e.g. a patent is more valuable if it covers more or lasts for longer).*

Corollary 3. *The rate of innovation is a monotonically increasing in the level of intellectual property rights, that is strengthening the degree of protection (and therefore increasing the reward for a winning firm) always increases the rate of innovation.*

Thus, in order for an open approach to be a better *production* model requires us to identify where one or other of the above propositions is in error.

7.1. **Innovating Theory.** Given the innate plausability of the first of the two propositions our focus must be on the second. In particular one can consider the two ends of the production equation: one can investigate (a) whether intellectual property imposes costs that openness does not and/or (b) whether the discrepancy in incentives (monetary or otherwise) between an open regime and an intellectual property regime is less substantial than initially imagined (in the crudest models, where pure nonrivalry is assumed, income for innovators is zero in the absence of intellectual property rights).[71]

his reputation and led to a flood of commissions"(Macleod, 1988, p. 104). Nevertheless the increasing prominence of 'knowledge' in the economy has brought these questions a new prominence and significance.

[70]This assumption is implicit in the literature on the subject of optimal patent design for, without it, in most of those models optimal patents would be infinitely long and broad.

[71]Such an assumption is equivalent to assuming instantaneous and costless imitation. Such an assumption, which is a natural one to make when focusing on other issues, is pervasive in the literature – appearing explicitly for example in Klemperer (1990); Hopenhayn and Mitchell (2001); Menell and Scotchmer (2005).

On the cost side there are various points to be made. With cumulative innovation the rights of new innovators may overlap with those of old. Combined with obstacles to perfectly efficient bargaining (such as imperfect information) exclusive rights may result in hold-up. This approach appears in both Bessen and Maskin (2006) (discussed above in Section 4) and Pollock (2006b). Both papers find that, in certain circumstances, it will be preferable to have an open, rather than an intellectual property rights, regime.[72]

One would also expect the level of componentization to play a role (for example, one would expect the degree of hold-up to increase with the level of 'componentization'. Componentization is used as a generic term here to denote the situation where a given product or idea combines or depends upon many previous ones (rather than a single one). As yet, there are very few papers that address the question of innovation, and innovation policy, in the area of componentized goods (and none that the author knows of which address componentized *and* cumulative innovation). Shapiro (2001) considers cross-licensing and patents pools and makes the general point that pools improve welfare when the patents are complements but harm welfare when the patents are substitutes. Lerner and Tirole (2004) develop a more complex model of patent pool arrangements seeking to provide some general guidelines as to when such pools are welfare improving. Meanwhile, Gilbert and Katz (2007), develop a patent race model for 'complex' technologies (those with many components) and investigate what the optimal division of profit should be in order to induce efficient R&D effort.[73]

A second option, also related to the cumulativeness of innovation, is that participation (production) at different innovation stages are linked – for example, one could have that participation at any given stage in the innovation 'ladder' is dependent on participation at the previous stage. In this case, intellectual property rights, by excluding innovators from participation at stage N, reduce those who can participate at future stages. In such a situation it is possible that all innovators lose out in the long run – even those who, by successfully obtaining intellectual property rights, gain in the short term. As a result the

[72]See also the model of Hunt (2006) who develops a simple model in which patents may reduce R&D.

[73]The componentization of production in an industry combined with the presence of intellectual property rights can lead to patent 'thickets' which obstruct innovation. Hall and Ziedonis (2001) provide evidence for this effect in the semiconductor industry while Bessen and Hunt (2007) do so for the software industry – in this area there is also the recent work of Noel and Schankerman (2006) which looks at the overall effect of patents in the software industry (focusing on large firms only) and while finding some negative impact of 'thicketiness' find an overall positive impact of patents on R&D.

level of innovation will be reduced compared to the situation without intellectual property rights.

Turning to income side of the equation the first point to consider is the possibility of up-front funding. With up-front funding either by rewards or by direct subsidy (research in universities for example) it is possible for work to be open ab initio *and*, at the same time, for their 'creators' to be guaranteed remuneration.[74]

Even without up-front funding it is often possible for creators to derive a substantial income by means other than by the use of exclusive rights. Of course, one must be careful here since the primary alternative to the use of intellectual property is not openness but secrecy. Thus, in considering the various methods by which remuneration can be obtained, we should confine ourselves to those mechanisms that are compatible with open production (that is those which ensure the knowledge produced is 'open').

The most prominent examples of such mechanisms arise where there exists a rival good which is complementary to the underlying knowledge.[75] Examples of such a complementary rival good include support services in relation to open source software, live performances in relation to 'open' music,[76] and access to attention in the case of advertising supported information provision.

We should also add a qualification to the implicit assumption of opposition between openness and intellectual property. It should be remembered that the relationship between the open 'commons' and the enclosed realm of intellectual property rights is not a purely antagonistic one. As intellectual property rights expire, the knowledge they cover flows into the public domain, increasing and enriching it. Conversely, it is a fact universally acknowledged that all creators must be in want of a rich and vibrant public domain on which to build and from which to derive new ideas. Of course, the history of intellectual property, or at least copyright, can provide many instances where this flow has been dammed or even reversed by sudden expansions in the scope or duration of rights (or even

[74]OECD (2005) figures indicate that in 2004 private firms accounted for approximately 53% of total expenditure R&D with the remainder coming from public sources. In the USA and Japan the private share is higher at 63% and 74% respectively. In Latin American by contrast the public share is the majority (NSF 2000). For work on alternative compensation systems and 'prize design' see Wright (1983); De Laat (1996); Kremer (1998); Shavell and van Ypersele (2001); Fisher (2004).

[75]The potential use of complementary goods as an alternative method of appropriation when intellectual property is weak found particular emphasis in the seminal article of Teece (1986) – revisited in a recent special issue of Research Policy(volume 35, number 8, October 2006).

[76]See, for example, Connolly and Krueger (2005); Mortimer and Sorenson (2005).

where such changes are usually applied equally to existing and prospective work thereby removing work from the public domain). Nevertheless the fact remains that, at least when not abused, the relationship can be a symbiotic one rather than one of rivalry and opposition.

7.2. **Conclusion.** From the above summary it should be clear that there are indeed reasons why the propositions, and their associated corollary, might fail, and for 'openness' to be good for innovation. That said, whilst progress is being made, there is, as yet, no fully articulated and intellectually coherent theory, or empirics, of open knowledge production that can convincingly demonstrate its advantages when compared to other approaches, such as those based on exclusive rights (intellectual property).

Furthermore, it is necessary to go beyond simple explanation, to examine in detail both (a) the various factors at work that influence the attractiveness (or not) of an open approach and (b) how these factors relate to the different types of subject matter. Is it, for example, the feasability of up-front funding, the presence of strong first-mover advantages, the level of transaction costs or the degree of componentization – among many other factors – that determine the advantages (and disadvantages) of an open approach vis-a-vis intellectual property? And are these factors constant or do they vary across disciplines? Are the same factors equally important in the production of pharmaceuticals and the development of operating systems – or, for that matter, online encyclopaedias? If not, as seems likely, then any general theory will need careful calibration to the specifics of the case at hand.

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