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Research vs. development: Optimal patenting policy in a three-stage model*

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To produce a new product/process firms have to go through two distinct stages. Research is discontinuous and stochastic: a prototype is a success (failure) with probability p $(1-p)$. Development is non-stochastic and continuous, quality improvements being a concave deterministic function of development inputs. The paper shows how patent policy affects market structure and welfare. Under a single-patent regime, granting patents to research prototypes is unambiguously welfare-improving, whereas under a multiple-patent regime granting protection only to developed products/processes may be more beneficial in so far as it reduces entry, which tends to be excessive under the prototype-protection regime.

Key words: Research; Development; Patents; Multi-stage games; Oligopoly

JEL classification: O31; L13

1. Introduction

An invention has to meet two main criteria in order to be granted a patent: it has to be *novel* and capable of *industrial applicability* (or in US patent law, *useful*). The issue of optimal novelty standards has been addressed in a series of recent contributions: in a previous issue of this *Review* La Manna, Macleod and De Meza [LMD (1989)] considered the welfare implications of manipulating the novelty standard by allowing for *multiple* patents to be granted to genuine inventors. Klemperer (1990) examined a similar problem in a horizontally differentiated good model and determined the optimal breadth of patents as the least inefficient market size for the patented good. Much less progress has been made on the modelling of the industrial applicability criterion [see, however, the models in Scotchmer and Green (1989) and La Manna (1992a) where minimum patentability standards are used to improve welfare].

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This paper considers a novel way of analysing the *industrial applicability* standard by modelling it as a binary choice between granting patents to either research prototypes or to developed products. This, of course, requires a model that draws an analytically meaningful distinction between research and development, in contrast with much of the existing theoretical literature on the economics of R&D which treats research and development as indistinguishable.[1]

The aim of the paper is to show that by modelling research and development as *different* stages one can both highlight new dimensions of the patent system and enrich the menu of patent policy instruments. Section 2 sketches the basic three-stage (research–development–output) game; sections 3 and 4 examine the welfare implications of granting patents to either research prototypes or to developed products under both single- and multiple-patent regimes. Section 5 concludes and suggests possible applications and extensions. All technical details are relegated to the Appendix.

2. A three-stage model of R&D

The empirical literature on R&D highlights two 'stylised facts': research is believed to be both *more uncertain* and *more discontinuous* than development.[2] The model described in this section embodies both these distinguishing features of R&D.

Firms take three decisions: (a) whether to pay a research fee, φ, that yields a probability p of producing a successful prototype of a new product/process; (b) to what extent, x, to develop the research prototype; and (c) how much final output, Q, to produce. Risk neutrality is assumed throughout.[3]

As I wish to locate a Cournot–Nash sub-game perfect equilibrium, I shall solve the above three-stage model anti-chronologically, starting with the final stage.

Stage 3: Production. Assume that the research lottery has been entered and has resulted in success for k firms. The Cournot–Nash equilibrium level of output for a typical firm i, Q_i^*, can be defined in terms of firm i's own cost of development, v_i, and of its competitors' development costs, $v_{-i} \equiv (v_1, \ldots, v_{i-1}, v_{i+1}, \ldots, v_k)$, i.e., $Q_i^* \equiv Q_i(v_i, v_{-i})$. The resulting gross profits (i.e., net

[1]A notable exception to the common practice of lumping research and development together is the model by Grossman and Shapiro (1987) in which two firms are engaged in a race to discover a new product. Unlike our model, in which entry is endogenous and research and development have different effects, in theirs industry structure is fixed and research and development are merely two phases of an identical process.

[2]For example, Freeman (1974, p. 226, Table 32) lists degrees of uncertainty associated with various types of innovation, starting with 'basic research' (highest uncertainty) and ending with 'minor technical improvement' (lowest uncertainty).

[3]Appendix A in LMD (1989) illustrates how the analysis can be amended to take into account risk aversion.

profits plus development costs, v_i) will be written as $\pi(v_i, v_{-i})$. It is assumed that the inverse demand function and the development cost function generate a gross profits function $\pi(\cdot)$ that is concave and strictly increasing in v_i. Notice that the above formulation allows for more than one patent to be granted (i.e., $k \geq 1$).[4]

Stage 2: Development. In order to make the model both interesting and realistic, it is assumed that the extent of the improvement of the product being developed, x_i, is a concave function of the cost of development, v_i : $x_i = x(v_i)$, $x' > 0$, $x < 0$. The model can accommodate both product and process innovations, depending upon whether x is interpreted as the size of the outward shift of the final-output demand curve or as the extent of the downward shift of the marginal cost curve.

Stage 1: Research. Given the optimal choices at the production and development stages, each firm has to decide whether to pay a research fee φ which buys a probability p of producing a successful research prototype.

This very simple characterisation of R&D takes to an extreme the two stylised facts mentioned above: development is non-stochastic and results in improvements commensurate to the investment in development inputs, whereas research is carried out under uncertainty and in the presence of a strong threshold effect. Unless a research fee φ is paid no new ideas can be produced, with expenditures in excess of φ yielding no increase in the probability of discovering a successful prototype.

3. Welfare effects of granting a single patent to either a research prototype or a developed product/process

In this section the patent system is assumed to be of the strict *tournament* type[5], in the sense that firms engaged in R&D compete for a *single* patent. The issue addressed here is *what* this single patent ought to be awarded to. Standard models of patent races ignore the question of whether the patent should be awarded to a research prototype (i.e., to the outcome of the research stage) or to a developed product/process (i.e., to the outcome of the development stage). This distinction, which is not captured by current models that formalise the notion of patent *breadth*[6], is of obvious policy relevance.

[4]For example, using the parametrisation A1-3 in the Appendix we obtain

$$\pi(v_i, v_{-i}) = \frac{1}{\beta}\left(\frac{\sum_{i=1}^{k} \theta v_i^{\alpha}}{k+\beta}\right)^{1-\beta/\beta}\left[\frac{k}{k+1}\theta v_i^{\alpha} - \frac{1}{k+1}\sum_{j\neq i}^{k} \theta v_j^{\alpha}\right]^2$$

[5]On tournament and non-tournament models of technological competition, see Beath et al. (1989).

[6]See Klemperer (1990) and the references cited therein.

To mention but one example, the biotechnology industry is plagued by the uncertainty regarding the very meaning of patentable matter[7]. Is the discovery of a DNA sequence with a mere hint of potentially beneficial effects sufficient ground for patentability, or should the claim to usefulness be substantiated by further development work?[8] Under a single-patent regime, using the sum of expected industry profits and consumers' surplus as the relevant welfare index, the answer turns out to be both simple and unambiguous:

Proposition 1. *Under free entry and a single-patent regime, higher welfare levels are attained by granting patents to research prototypes rather than to developed products/processes.*

The rationale for Proposition 1 is quite intuitive. The key difference between a Single-patent Research-based (SR) regime and a Single-patent Development-based (SD) regime is that under the latter firms have to invest in development *before* knowing whether they have been awarded the patent. The SD regime lowers the expected return from development and, as compared to the SR regime, results in fewer firms entering the race (thus reducing the probability of a successful prototype being produced at all) and in less investment in development (thereby lowering the rate of technical change). It should be noted that current patent rules approximate a research-based regime, in so far as the mere possibility of industrial application is sufficient[9] for awarding a patent, provided, of course, other relevant criteria (inventive step, novelty, etc.) are satisfied.

More formally, assuming that in the event of k firms succeeding in producing a patentable good each has a probability of $1/k$ of being awarded the patent, expected profits under the SR and SD regimes will be respectively:

$$\mathrm{E}\{\pi^{\mathrm{SR}}\} \equiv p \sum_{i=0}^{N-1} \binom{N-1}{i} p^{1} q^{N-1-i} \frac{1}{i+1} \max_{v} (\pi(v) - v) - \varphi, \tag{1}$$

[7]The European Commission's Directive on the legal protection of biotechnological inventions [European Commission (1988)] aims at providing a definition of patentable matter. See also La Manna (1992b) for an empirical analysis of the impact of the Directive on the British biotechnology industry.

[8]According to a leader in *The Economist* (1992) thousands of patent applications on *expressed-sequence tags* (ESTs) are currently filed with the US Patent Office. ESTs are copies of gene fragments and can be produced by the hundreds each month with very little 'development'. *The Economist* suggests that patent applicants 'should be required to show the use to which they think [the product of their biochemical] might eventually be put'. This is very close to suggesting that, in the terminology of section 3, a multiple-patent development-based regime may perform better than a research-based one. (I owe this reference to a referee.)

[9]European patent law seems to be more permissive in the application of the criterion of industrial applicability than US law; see, for example the discussion of the Brenner vs Manson in Miller and Davis (1990). (I owe this reference to a referee.)

$$\mathrm{E}\{\pi^{\mathrm{SD}}\} \equiv p \max_{v} \sum_{i=0}^{n-1} \binom{N-1}{i} p^{1} q^{N-1-i} \frac{1}{i+1} (\pi(v)-v) - \varphi, \tag{2}$$

where $q \equiv 1-p$, N (n) is the number of entrants under the SR (SD) regime and $\pi(v)$ is gross profits. (1) and (2) can written as

$$\mathrm{E}\{\pi^{\mathrm{SR}}\} \equiv \frac{1-q^{N}}{N} \max_{v} (\pi(v)-v) - \varphi, \tag{3}$$

$$\mathrm{E}\{\pi^{\mathrm{SD}}\} \equiv \frac{1-q^{n}}{n} \max_{v} \left[\pi(v) - \frac{pn}{1-q^{n}} v \right] - \varphi. \tag{4}$$

Notice that, as the unit cost of development under the SD regime [i.e., $pn/(1-q^n)$] exceeds the cost of development under the SR regime ($\equiv 1$) for $\forall n \geq 2$,[10] firms will invest more in development under the latter regime, for $\pi(v)$ is concave in v. Defining net social welfare under the two regimes as the expected sum of consumers' surplus and net industry profits, in obvious notation:

$$\mathrm{E}\{W^{\mathrm{SR}}\} \equiv (1-q^{N})[CS(v)+G(v)-v] - N\varphi, \tag{5}$$

$$\mathrm{E}\{W^{\mathrm{SD}}\} \equiv (1-q^{n})[CS(v)+G(v)] - npv - n\varphi. \tag{6}$$

Assuming that the cost of research φ is such that expected net profits are zero under both regimes, it follows that

$$\mathrm{E}\{W^{\mathrm{SR}}\} \equiv (1-q^{N})CS(v) > (1-q^{n})CS(v) \equiv E\{W^{\mathrm{SD}}\}. \tag{7}$$

Inequality (7) follows from the fact that consumers' surplus is increasing in v and that in order for expected profits to be zero under both regimes the free-entry number of firms under the SR regime, N, must exceed n (the free-entry number of firms under the SD regime), for $(1-q^k)k$ is decreasing in k.[11]

[10]
$$\frac{1-q^{n}}{p} \equiv \sum_{i=1}^{n} \binom{n}{i} p^{i-1} q^{n-i} \equiv \sum_{i=0}^{n-1} \binom{n}{i+1} p^{i} q^{n-i-1} \equiv \sum_{i=0}^{n-1} \binom{n-1}{i} \frac{n}{i+1} p^{i} q^{n-i-1}$$
$$\equiv n \sum_{i=0}^{n-1} \binom{n-1}{i} \frac{1}{i+1} p^{i} q^{n-i-1} < n.$$

[11] $\dfrac{(1-q)^{k}}{k}$ is decreasing in k iff $1 > (1-p)^{k}(1+pk)$.

Notice that as the RHS of (f11) reaches a maximum at $p^* = -\log(1-p^*)(1+kp^*)$, (f11) holds a fortiori if $1 > (1-p^*)^k\ (1+p^*k)$, i.e., if $-\log(1-p)/p > (1-p)^k$, which can be seen to hold by expanding $\log(1-p)$ in power series: $1 + p/2 + p^2/3 + \ldots > (1-p)^k$.

4. Welfare effects of granting multiple patents to either research prototypes or developed products

The issue of whether the patent system should retain its winner-takes-all feature or should dilute the returns to R&D by rewarding also 'fast losers' has been examined in LMD (1989). The main result there was that there are circumstances (e.g., constant returns in production and variable patent life) under which granting *multiple* patents raises welfare as compared to the current single-patent system. In this section I shall determine the socially optimal criterion of industrial applicability in a multiple-patent system by examining whether multiple patents ought to be granted either to research prototypes or to developed products.

Consider, for instance, the multi-billion seeds industry. Under the current system any change, however trivial, in one of the many descriptors of a plant variety[12] is deemed sufficient for the award of a breeder's right. Hence, the patent regime is clearly multiple-patent. Would welfare be raised by introducing patentability standards requiring more development being undertaken (establishing, for example, substantial improvements on existing varieties)?

It turns out that, unlike the single-patent regime, granting multiple patents to research prototypes rather than to developed products does *not* necessarily lead to a welfare improvement. The interplay of three factors determines whether a research-based regime performs better than a development-based system: (i) the productivity of the development process; (ii) the cost of research, φ; and (iii) the probability of research discoveries, p. Intuitively, if the probability of discovery relative to the cost of research, p/φ, is high and thus entry is of little social benefit, a development-based regime by reducing the returns to R&D and thus discouraging entry may lead to higher welfare than a research-based regime.

4.1. *A Multiple-patent Research-based* (*MR*) *regime*

Under a Multiple-patent Research-based regime all firms that succeed at the research stage are granted a patent on their research prototypes.[13] Thus firms know the structure of the final-output market *before* committing resources to the development of their successful prototypes.

Let $\pi_i(k)$ be firm i's profits at a symmetric Cournot–Nash equilibrium in a $(k+1)$-firm industry where development expenditure, v, is chosen non-cooperatively:

[12] According to European patent rules, over fifty descriptors are required to distinguish between the various varieties of barley.

[13] LMD (1989) discuss how plagiarists can be prevented from filing for patents under a multiple-patent regime.

$$\pi_i(k) \equiv \max_{v_i} [\gamma(v_i, v^*_{-i}; k+1) - v_i], \tag{8}$$

where $\gamma(v_i, v^*_{-i}; k+1)$ is gross profit from the combined research and development programme in a $(k+1)$-firm Cournot oligopoly.

Let $h(p, m, k)$ be the probability that k out of $m-1$ entrants succeed at the research stage (or, alternatively, the probability that, conditional on one firm out of m having succeeded in producing a prototype, k others also succeed):

$$h(p, m, k) \equiv \binom{m-1}{k} p^k (1-p)^{m-1-k}. \tag{9}$$

Therefore under an MR regime the expected net payoff for an entrant is

$$\mathrm{E}\{\pi^{\mathrm{MR}}\} \equiv p \sum_{k=0}^{N-1} h(p, N, k)\pi(k) - \varphi = 0, \tag{10}$$

where N is the free-entry number of entrants under an MR regime. It is worth noting that the MR regime is the mirror image of the standard winner-takes-all model of patents (in which no distinction is drawn between R&D). Under the latter, the value of the prize (the single patent-holder monopoly profits) does not depend on the number of entrants, but the probability of being awarded the patent does. By contrast, under an MR regime, the probability of discovery p is independent of entry, but the value of the prize depends on the structure of the final-output market and thus ultimately on the number of entrants.

We can prove the following

Proposition 2. Let $\chi(p, N)$ be the cost of research such that under a free-entry equilibrium all N entrants earn zero profits (with N integer); then for any $N \geq 2$ $\chi(p, N)$ reaches a maximum at $p^0(0 \in 1)$.

Proposition 2 states that the relationship between the free-entry number of firms N and the probability of discovery p is not monotonic: any increase in p beyond p^0 will *reduce* each entrant's gross profits. Or, alternatively, there is always a level of research costs, $\bar{\varphi}$ such that $\chi(p^0, N) > \bar{\varphi} > \chi(1, N)$. This means that at $\varphi = \bar{\varphi}$ as p varies there is a reswitching in the free-entry number of firms. Fig. 1 illustrates this case for $N=2$. The economic rationale for this reswitching is simple. Suppose that discoveries are 'easy' (i.e., $p^{\mathrm{H}} < p \leq 1$) and that research inputs $\bar{\varphi}$ are so expensive that a free-entry equilibrium sustains only one firm. As discoveries become slightly more difficult, but still 'easy' (i.e., $p^{\mathrm{M}} \leq p \leq p^{\mathrm{H}}$), entry may become profitable for two firms, their profits being, of course, a weighted average of monopoly and duopoly profits. As the weight attached to monopoly profits $p(1-p)$ is relatively small, duopoly

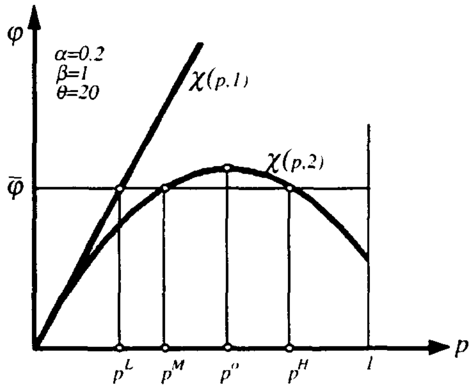

Fig. 1

profits may be large enough to make entry profitable, recalling that for $p^{\mathrm{H}} < p \leq 1$ a free-entry monopoly earns super-normal profits. As p falls, expected gross profits also decline, with monopoly profits becoming relatively more important. Eventually a point is reached (p^{L} in fig. 1) where a free-entry equilibrium will sustain again only one firm. The reswitching follows from the changing relative importance of the two contrasting effects of a reduction in p: a decrease in the probability of discovery increases the probability that a firm will fail, but, conditional on it having succeeded, it increases the probability that it will operate in a more concentrated market.[14]

The gross profit function $\chi(p, N)$ has another interesting feature, as stated in the following

Proposition 3. Let $p^0 \equiv \operatorname{argmax} \chi(p, N)$ *and* $p^* \equiv \operatorname{argmax} \chi(p, N+1)$*; then* $p^0 > p^*$.

Proposition 3 says that the higher the number of entrants, the lower the 'turning-point' level of the probability of success.

The significance of these two propositions can be best appreciated by providing a different interpretation of the above model. Suppose that N firms, who behave non-cooperatively in the final-output market, decide to finance a jointly-owned research lab that can produce research prototypes that can be turned into a marketable product either with certainty (*perfectly reliable prototypes*) or with probability $p < 1$ (*unreliable prototypes*). Proposition 2 implies that all N firms will agree on instructing the lab to turn out the *less* reliable prototype. Proposition 3 says that the larger the number of firms funding the research lab, the less reliable the profit-maximising

[14]This interpretation was suggested by a referee.

prototype will be. Consider the case $N=2$ and let π_1 and π_2 be respectively monopoly and duopoly profits. According to Proposition 2:

$$p(1-p)\pi_1 + p^2\pi_2 > \pi_2. \tag{11}$$

Let $\pi_1 \equiv (1+\sigma)\pi_2$ with $\sigma > 1$ to allow for the dissipation of profits engendered by competition; then maximising the l.h.s. of (11) w.r.t. p yields

$$p^0 = \frac{1+\sigma}{2\sigma} < 1, \quad p^0(1-p^0)\pi_1 + p^{0^2}\pi_2 > \pi_2. \tag{12}$$

thus confirming that the two firms will have the lab turn out the *less* reliable prototype. More perversely still, the same result obtains even if producing a less than perfectly reliable prototype is (slightly) *more costly* than producing a perfectly reliable one. Proposition 3 warns against the possible side-effects of lowering the cost of research (e.g. by subsidising multinational research consortia), in so far as the resulting increase in membership can produce a deterioration in the quality of research.[15]

4.2. *Welfare effects of entry under a Multiple-patent Research-based regime*

Should entry be encouraged (restricted) through a research subsidy (tax)? It turns out that the crucial factor is the probability of discovery, p, relative to the cost of research, φ. Suppose that p/φ is so low that even a single entrant would find it marginally unprofitable to enter the (solitary) R&D race. Then an entry-inducing research subsidy would clearly raise welfare. Conversely, if $p=1$, Proposition 4 below shows that the standard excess-entry result applies, and thus an entry-reducing tax would improve welfare. Consider the certainty case first. The model then resembles the non-tournament model of Dasgupta and Stiglitz (1980), where R&D expenditure x lowers constant marginal cost [i.e., total cost equals $x + c(x)Q$; $c' < 0$]. They show that when both the demand function and cost-reducing R&D function are iso-elastic, free entry generates too many firms. It may be of interest to note that the same result applies with a linear demand curve, irrespective of the shape of the R&D cost-reducing function, when research costs are fixed and cost reductions are a function of development inputs.

[15]This example provides a perverse interpretation of the popular complaint about the unsatisfactory level of industrially applicable research in the UK. Interpreting the education system as the nation's research lab and British industry as (an admittedly indirect) determinant of the quality of research (e.g., by paying low salaries to applied scientists), the above example suggests that the low percentage of research prototypes turned into marketable products is the direct implication of profit maximisation by non-colluding oligopolists. Notice also that the same result applies, albeit under stricter conditions, even if a final-output competitor (e.g., a Japanese firm) is committed to perfectly reliable prototypes.

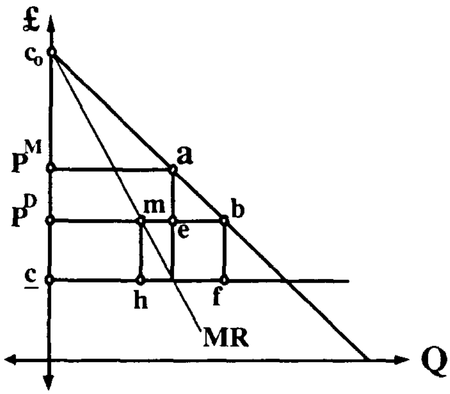

Fig. 2

Proposition 4. Under certainty, linear demand curve and constant marginal cost, a Cournot equilibrium sustains too many firms, irrespective of the shape of the R&D cost-reducing function.

The logic of Proposition 4 is simple and is illustrated in fig. 2. Suppose that under duopoly marginal cost is reduced from c_0 to, say, $\underline{c}$. The erosion of supernormal profits due to free entry guarantees that the industry cost of both research, 2φ, and of development, $2v^D$ equals the area $p^D bf\underline{c}$. It is simple to show that under quantity competition the savings in fixed cost and in (duplicated) development cost ($\equiv p^D mh\underline{c}$) brought about by a switch from duopoly to monopoly exceed the welfare loss due to the higher price ($\equiv abe$). Of course, a monopolist would reduce marginal cost by a larger amount and would spend more on development. This, however, merely tips the balance even more towards monopolisation, for profits would obviously increase and the welfare loss would be reduced (because of the lower price). Under the above assumptions, we may conclude that an entry-reducing tax on research would improve welfare.

The above result does not survive as soon as uncertainty is introduced (i.e., $p<1$). Using the simple parametrisation of a linear demand curve, marginal-cost-reducing development and an iso-elastic development cost function, we can construct a simple diagram that summarises how entry can be manipulated so as to improve welfare under uncertainty. First, some notation. Let $\Phi(p,N)$ be the marginal net social benefit of the Nth firm. For any given N, $\Phi(p,N)=0$ defines a curve in the (p,φ) space along which the marginal gross benefit of the Nth firm equals the cost of entry, φ. Thus anywhere above (below) $\Phi(p,N)=0$ there should be less (more) entry. Next let $\mathrm{E}\pi(p,\varphi,N)=0$ be a curve in the (p,φ) space showing the combinations of p and φ that yield zero profits at an N-firm equilibrium. By construction, anywhere above

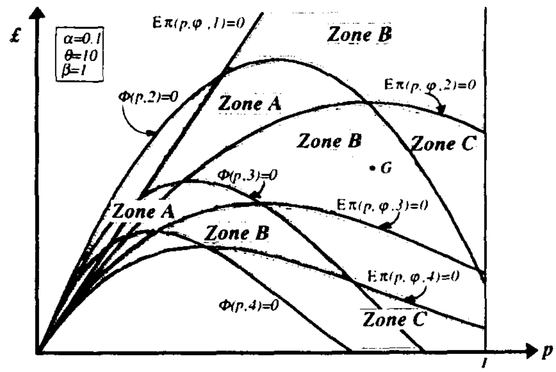

Fig. 3

(below) $E\pi(p,\varphi,N)=0$ entry by the Nth firm would be unprofitable (generate supernormal profits). Superimposing a family of $\Phi(p,N)=0$ curves onto a family of $E\pi(p,\varphi,N)=0$ curves we can compare the free-entry number of firms, N^0, with the socially-optimal number of firms, N^w. Consider, for example, point G in fig. 3. As G lies below $E\pi(p,\varphi,2)=0$ and above $E\pi(p,\varphi,3)=0$, at G two firms will be active, each earning supernormal profits. Moreover, as G lies below $\Phi(p,2)=0$ and above $\Phi(p,3)=0$, entry ought not to be encouraged. The (p,φ) space can then be divided into three zones:

Zone A: $N^w>N^0$. When discoveries are 'difficult' relative to the cost of research, a free-entry equilibrium does not generate enough research units.
Zone B: $N^w=N^0$. Welfare cannot be improved by manipulating entry.
Zone C: $N^w<N^0$. In spite of the rugged contours of Zone C (due to the integer constraint), we can infer that when p/φ is 'high', then even under uncertainty a free-entry Cournot–Nash equilibrium sustains *too many firms.*

In conclusion, if the probability of discovery is high as compared to the cost of research, a Multiple-patent Research-based regime will yield *excessive research* and *too little development.*

4.3. Multiple-patent Development-based regimes

By contrasting Research- vs. Development-based regimes we can highlight a feature of the patent system that has been ignored by traditional patent models. These models, in fact, by defining patents as the reward of the *combined* research and development programme are prevented from endowing patents with the role of altering the allocation of resources *between* research and development.

The point at issue is simple: under an MD regime a firm that succeeds at the research stage has to commit resources to develop its prototype without the benefit of knowing how many other firms have also succeeded. Thus, the intensity of development depends on the *expected* number of competitors in the final-output market[16]. By contrast, under the MR regime, as patents are awarded to prototypes, market structure is revealed *before* resources are committed to development. Under the MD regime, firms that succeed at the research stage would benefit from being able to signal their type but cannot do so without giving away their (unpatentable) information, whereas the MR regimes allows them to reveal their true type. In this sense, the Patent Office can use patents as *information signals*, thereby affecting market structure. In fact, the effect of granting patent protection to prototypes is to increase the expected return from investing in development, thus encouraging entry.

Using the same notation as before, the expected net profits for a typical firm i under an MD regime can be written as

$$\mathrm{E}\{\pi^{\mathrm{MD}}\} \equiv p \max_{v} \left[\sum_{i=0}^{n-1} \binom{n-1}{i} p^i q^{n-1-i} \gamma(v,k) - v \right] - \varphi. \tag{13}$$

The key feature of (13) is that the profit-maximising level of development expenditure, v^{MD}, depends on the *expected* number of firms succeeding at the research stage and thus, ultimately, on the probability of success, p.[17] In contrast, under the MR regime development expenditures are determined knowing the *actual* number of successful firms ($\equiv$ number of patents).

In assessing the relative merits of the two regimes, a key role is played by *uncertainty* and *entry*. First, notice that under certainty ($p=1$) the distinction between the two regimes vanishes.[18] As to the effect of entry, we know from section 4.2 that especially when the p/φ ratio is 'high' the MR regime induces excess entry. The MD regime, instead, will always sustain fewer firms than the MR regime. To ascertain if a switch to the entry-reducing MD regime may increase welfare, we have to establish first the following

Proposition 5. Subject to a mild regularity condition, if entry is fixed, then

[16]Let $\mathrm{E}\{\pi^{\mathrm{MR}}\}$ be the expected net profit of a typical firm under the MD regime, i.e.

$$\mathrm{E}\{\pi^{\mathrm{MR}}\} \equiv p \max_{v} \left[\sum_{k=0}^{n-1} \binom{n-1}{k} p^k q^{n-1-k} \gamma(v,k) - v \right] - \varphi.$$

Obviously, the level of development expenditure that maximises $\mathrm{E}\{\pi^{\mathrm{MR}}\}$, v^{MR}, depends on the *expected* number of firms succeeding at the research stage.

[17]Under the *MD* regime firms can be assumed to belong to either of two 'types': 'successful' and 'unsuccessful'. Upon payment of the research fee, φ each entrant knows her own type, but not the type of any other firm. As each firm knows the probability distribution from which types are drawn (and each firm knows that every firm knows it, i.e., p is common knowledge), the value of n such that $\mathrm{E}\{\pi^{\mathrm{MR}}\}=0$ defines the Bayesian equilibrium of the game.

[18]The same does not apply to single-patent regimes which do *not* converge at $p=1$.

Table 1

Switch-over value of probability of succes in reasearch: Duopoly under MD regime more efficient than triopoly under MR for $p > \tilde{p}$.

	$\beta = 0.5$ Convex demand	$\beta = 1$ Linear demand	$\beta = 2$ Concave demand
$\alpha = 0.1$	$\tilde{p} = 0.635$	$\tilde{p} = 0.489$	$\tilde{p} = 0.34$
$\alpha = 0.2$	$\tilde{p} = 0.760$	$\tilde{p} = 0.534$	$\tilde{p} = 0.362$
$\alpha = 0.25$	$\tilde{p} = 0.784$	$\tilde{p} = 0.564$	$\tilde{p} = 0.377$

the MR regime is always superior to the MD regime, with welfare levels under the two schemes converging at $p = 1$.

The key to Proposition 5 is that for a given number of firms, per-firm expenditure on development is an unambiguous and increasing index of welfare and, of course, is lower under the MD regime. If entry is not exogenously fixed, Proposition 5 can be read as saying that at a free-entry equilibrium the MD regime sustains fewer firms than the MR regime.

Combining Propositions 2, 4 and 5, we finally obtain

Proposition 6. *Provided discoveries are not 'too difficult', a switch from the MR regime to the MD regime raises welfare.*

Proposition 6 states that, unlike a single-patent regime, under a multiple-patent scheme the allocation of resources *between* research and development can be improved by means of an entry- reducing increase in costs. Much of the force of Proposition 6 would be lost if it turned out that the 'maximum' degree of uncertainty necessary for the proposition to hold (i.e. $\tilde{p}$) were close to 1. This would mean that the MR regime would perform better than the MD scheme for $\forall p \; 0 < p < \tilde{p} \approx 1$. To locate the switch-over value of p, we have to parametrise. Using the functional forms described in the appendix, for any given N, the critical value of p is determined by two parameters: the elasticity of the cost-of-development function, $1/\alpha$ and the demand curvature parameter β, as shown in table 1.

The above comparison between research- and development-based multiple-patent regimes provides some theoretical justification for more stringent standards of industrial applicability be applied to those fields where multiple-patenting is the norm. To add another example to the seed industry case mentioned above, consider the recent practice of filing patents for human genes. Given the apparent ease of discovery,[19] there seems to be a case for requiring inventors to engage in some form of development prior to filing for patent protection.

[19]Some genetic engineering labs are reported to be isolating up to thirty potentially patentable human genes *every* day.

5. Extensions and applications

The above analysis suggests that under a multiple-patent scheme the only reason why a development-based regime can outperform a research-based one is that the latter encourages wasteful entry. The same welfare analysis applies also to other policies that the Patent Office can implement to restrict entry. I shall briefly consider two of these. One way of restricting entry is to impose a minimum standard of development, $x_{\min}$. Alternatively, the Multiple-patent Research-based regime can be 'fine-tuned', as suggested in LMD (1989, Appendix A), by granting patents on research prototypes only for the first s inventors ($N \geq s \geq 1$), i.e., the expected profits for an entrant under this Modified MR scheme (MMR) would be:

$$\mathrm{E}\{\pi_i^{\mathrm{MMR}}\} \equiv \sum_{i=1}^{s} \binom{N}{i} \frac{i}{N} p^i q^{N-i} \pi_i + \sum_{i=s+1}^{N} \binom{N}{i} \frac{s}{N} p^i q^{N-i} \pi_s - \varphi.$$

The maximum number of patentees s could then be interpreted as an index of patent *scope*[20]. In this light, the single-patent ($s=1$) and multiple-patent ($s=N$) regimes can be seen as the two extremes of a continuous range.

The distinction between research and development as modelled in this paper can be applied to R&D joint ventures: should collaboration be encouraged at the research or at the development stage (or at both)? A full analysis of this interesting issue is matter for future research.

Appendix

Demand:

$$P = P_0 - \left(\sum_{i=1}^{M} Q_i \right)^{\beta}, \quad M = N, n. \tag{A.1}$$

Cost:

$$C_i = (c_0 - x_i) Q_i + v_i. \tag{A.2}$$

Development:

$$x_i = \theta v_i^{\alpha}. \tag{A.3}$$

The above assumes that improvements brought about by development take the form of a downward shift of the pre-invention marginal cost c_0. Alternatively, it can be assumed that development shifts the pre-invention inverse demand curve by x (i.e., $P = P_0 + x - (\Sigma Q_i)^{\beta}$). To save on notation, I

[20]This interpretation has been suggested by a referee.

shall assume that without development production is marginally unprofitable, i.e. $c_0 = P_0$.

Proof of Proposition 2

Let $\chi(p,N) \equiv \sum_{i=0}^{N} \binom{N}{i} p^i q^{N-1} \max_{v_i}\{\gamma(v_i, v_{-i}) - v_i\}$. It is easy to establish that there exists a value of p, $p^0 \in (0,1)$, such that

$$\left.\frac{\mathrm{d}\chi(p,N)}{\mathrm{d}p}\right|_{p=p^0} = 0. \tag{A.4}$$

Differentiating $\chi(p,N)$ w.r.t. p we obtain:

$$\frac{\mathrm{d}\chi(p,N)}{\mathrm{d}p} = (1-p)^{N-1}\Pi_1 + \sum_{i=1}^{N-1} \binom{N-1}{i} p^i (1-p)^{N-1-i}[\Pi_{i+1} - \Pi_i].$$

As $\mathrm{d}\chi(p,N)/\mathrm{d}p$ is continuous and at $p=0$ ($p=1$) it takes on the value $\Pi_1 > 0$, ($[\Pi_N - \Pi_{N-1}] < 0$) there exists a $p^0 \in (0,1)$ such that (A.4) is satisfied. Straightforward substitution yields that at $p = p^0$

$$\operatorname{sign}\frac{\mathrm{d}^2\chi(p)}{\mathrm{d}p^2} = \operatorname{sign}\left\{-q^{N-1}(N-1)[\Pi_1 - \Pi_2] - \sum_{i=1}^{N-2}\binom{N-1}{i} p^i q^{N-1-i}(N-1-i)\Pi_{i+1}\right\} < 0,$$

thus proving that $\chi(p,N)$ is concave with a maximum at $p^0 \in (0,1)$.

Proof of Proposition 3

To establish Proposition 3 it suffices to show that $\mathrm{d}\chi(p, N+1)/\mathrm{d}p|p = p^0 < 0$, where p^0 is defined by (A.5).

$$(1-p^0)^{N-1}\pi_1 + \sum_{i=1}^{N-1}\binom{N-1}{i} p^{0^i}(1-p^0)^{N-1-i}[\pi_{i+1} - \pi_i] = 0. \tag{A.5}$$

Multiplying (A.5) by $(1-p^0)$ and substituting into $\mathrm{d}\chi(p,N+1)/\mathrm{d}p$, we obtain that at $p = p^0$:

$$\frac{\mathrm{d}\chi(p,N+1)}{\mathrm{d}p} = -\sum_{i=1}^{N-1}\binom{N-1}{i} p^i (1-p)^{N-1}[\Pi_{i+1} - \Pi_i]$$

$$+\sum_{i=1}^{N-1}\binom{N}{i}p^i(1-p)^{N-i}[\Pi_{i+1}-\Pi_i]+p^N[\Pi_{N+1}-\Pi_N]$$

$$\equiv\sum_{i=1}^{N-1}\left[\binom{N}{i}-\binom{N-1}{i}\right]p^i(1-p)^{N-i}[\Pi_{i+1}-\Pi_i]+p^N[\Pi_{N+1}-\Pi_N]$$

$$\equiv\sum_{i=1}^{N-1}\binom{N}{i}\frac{i}{N-i}p^i(1-p)^{N-i}[\Pi_{i+1}-\Pi_i]+p^N[\Pi_{N+1}-\Pi_N]<0.$$

Proof of Proposition 4

Using the functional forms (A.1)–(A.3) and assuming for simplicity that demand is linear ($\beta=1$), profits and welfare under an MR regime can be written as

$$\pi_N^{MR}=\frac{1-2N\alpha}{2N\alpha}v_N^{MR}, \tag{A.6}$$

$$W_N^{MR}=\frac{N}{4\alpha}v_N^{MR}+N\pi_N^{MR}, \tag{A.7}$$

where

$$v_N^{MR}=[2\alpha N\theta^2/(N+1)^2]^{1/1-2\alpha}.$$

Let $N+1$ be the free-entry number of firms under an MR regime, i.e., $N+1$ satisfies:

$$\varphi=\frac{1-2\alpha(N+1)}{2\alpha(N+1)}v_{N+1}^{MR}. \tag{A.8}$$

Using (A.6) and (A.8), the inequality to be established, $W_N^{MR}>W_{N+1}^{MR}$, can be written as

$$\frac{N^2+3N+2-4\alpha(N+1)}{N^2+4N+1-4\alpha(N+1)N}>\frac{v_{N+1}^{MR}}{v_N^{MR}}=\left[\frac{(N+1)^3}{N(N+2)^2}\right]^{1/1-2\alpha}. \tag{A.9}$$

Taking into account that the r.h.s. of (A.9) reaches a maximum at $\alpha=0$ and that setting $\alpha=\frac{1}{2}$ lowers the l.h.s., the above inequality holds if

$$\frac{N}{N^2+2N-1} \geq \frac{(N+1)^2}{N(N+2)^2}$$

which holds for $\forall N$.

Proof of Proposition 5

If entry is exogenously fixed at μ, welfare is increasing in expected development expenditure and thus the MR regime is socially preferable to the MD regime iff $E\{v^{MR}\} > E\{v^{MD}\}$. Let $\mu = 2$ and

$$v_1^{MR} \equiv \text{argmax}[\gamma(v,1) - v], \quad v_2^{MR} \equiv \text{argmax}[\gamma(v,2) - v],$$

$$v^{MD} \equiv \text{argmax} p\{(1-p)\gamma(v,1) + p\gamma(v,2) - v\}.$$

To establish that $E\{v^{MR}\} \equiv p(1-p)v_1^{MR} + p^2 v_2^{MR} > v^{MD}$, it suffices to show that

$$\tau \equiv (1-p)\gamma'[(1-p)v_1^{MR} + pv_2^{MR}, 1] + p\gamma'[(1-p)v_1^{MR} + pv_2^{MR}, 2] < 1,$$

i.e., using the mean value theorem and recalling that $\gamma'(v,1) = \gamma'(v,2) = 1$,

$$\tau \equiv 1 + (1-p)p(v_1^{MR} - v_2^{MR})[\gamma''(\xi_2, 2) - \gamma''(\xi_1, 1)].$$

Therefore Proposition 5 holds if the following regularity condition is satisfied:

$$\gamma''(\xi_2, 2) < \gamma''(\xi_1, 1).$$

Proof of Proposition 6

We know that if there is no uncertainty ($p = 1$) the MD regime is indistinguishable from the MR regime. Let φ^0 be the research cost such that under either regime zero profits are earned by N^0 firms (with N^0 being an integer). In view of Proposition 4, any entry-reducing change would improve welfare. We have to show that the same applies under uncertainty ($p < 1$). Let the probability of discovery fall from 1 to, say, $\tilde{p} = 1 - \varepsilon$, where ε is small. Because of Proposition 2, at $\tilde{p}$ profits under the MR regime are strictly positive. Let $\tilde{\varphi}$ ($> \varphi^0$) be the cost of research that ensures that N^0 firms earn zero profits under the MR regime. Proposition 5 implies that at $(\tilde{p}, \tilde{\varphi})$ each of the N^0 firms would incur a loss under the MD regime. Therefore at $(\tilde{p}, \tilde{\varphi})$ a free-entry equilibrium will sustain $N^0 - 1$ firms under the MD regime. Taking into account that (i) as $\tilde{p}$ is close to unity, net welfare levels under each regime are 'close'; (ii) for $p = 1$ net welfare is decreasing in N and (iii) the

$N^0 - 1$ firms active under the MD regime earn supernormal profits, welfare levels will be higher under the MD regime.

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