How should the gene be patented? Notes toward an economic model

Preliminary draft
For discussion

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Abstract

Patenting may speed up genetic research when small inventors face high research and development costs and also face large rivals that produce at declining marginal costs. Even with patents, however, small inventors may turn down socially beneficial projects when they believe that R&D spending will advance their rivals' research more than their own. [H41, I18]

Introduction

Artificial genes may transform an economy on a grand scale, as did the shrinking computer chip. Innovations in genetic engineering that improve the quality of the product include vaccines against hepatitis B, malaria and influenza. Combining genes from the ebola and human immunodeficiency viruses may yield a hybrid that cures cystic fibrosis (Weiss, 2001). By cloning, firms can cheaply make more of such substances as hormones, interferon (proteins that can slow viruses), and cytokines (which inform lymphocytes about the type of infection that they must ingest). Yet even a valuable genetic innovation may not be realized, since the idea behind it is a global public good. Inventors may balk unless government guarantees that it will convert the idea to a private good, via a patent, so that they can profit from hard work.

Patenting itself is a mixed blessing, however, for two reasons.

First: Patenting may delay the rate at which intellectual breakthroughs occur, since the idea itself cannot be patented. The thinker cannot claim a rent for her idea from builders who would embody the idea in products or processes that can be patented. The builder has no reason to pay for an idea until he has understood it; and then he need not pay for it, since understanding amounts to ownership (Arrow, 1974). But the builder can judge the value of a prototype-in-progress that embodies the idea – for example, the blueprint design of a noiseless jet. The builder can thus negotiate a fair payment to the thinker while she is building the prototype. Patenting may thus induce her to spend more time creating labor or physical capital that she can rent to builders – and less time creating ideas. Since she receives a rent for the blueprint, she might as well design it quickly, by embodying an already-existing idea.

More precisely, consider an idea as a directed arrangement of k concepts drawn from n in the mind. The probability of a random invention of the idea reflects the probability of choosing the correct k concepts of n and then rearranging the k concepts in the right order. The probability of randomly inventing the idea is thus

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$$\frac{1}{\binom{n}{k}}\frac{1}{k!} = \frac{(n-k)!}{n!},$$

which is smaller for more complex ideas (that is, ideas with more concepts k).

In a given period of time, the motivated thinker can improve upon this probability. If she bears in mind her purpose in creating the idea, then she can select and arrange the k concepts more quickly than would a stochastic process. She cannot claim a rent for her half-conscious algorithm for creating the idea; that is, she receives no rent on her motivation for creating the idea. Patenting may thus induce her to spend less time creating ideas – and more time designing products or processes that embody existing ideas.

This problem need not be severe for simple ideas – i.e., ideas that incorporate only a few concepts that are all so well-known that they can be quickly selected from the environment of n concepts. Because the thinker can create the idea quickly, she may do so in order to claim a rent on the idea's execution. For example, the thinker may not be able to collect on her idea of an auto engine that burns fuel cleanly by recycling products of combustion; but she may be able to collect on a prototype of the engine. This is because the prototype is harder to produce than the simple idea. Incorporating only about six concepts, the idea may occur to anyone, so that it has little scarcity value; but building the prototype requires training and experience, which are costly to acquire. Simple ideas may be invented in any event – and may even occur as random events. Thus the social loss in patenting may be greatest when thinkers reallocate time from creating complex ideas to creating material designs for existing ideas. Unfortunately, this reallocation may well occur, since the thinker knows that more complex ideas would demand more time from her.[2]

In addition to discouraging the creation of complex ideas, patenting may also generate a social loss through market power that distorts the allocation and the distribution of resources over time. Consider consumers who may be willing to pay a lot for the innovation but are too poor to do so. Particularly for an innovation that would prevent the spread of a communicable disease among them, they may object that a stiff patent fee is unfair and inefficient. These notes will address that broad question.

Patenting an artificial gene can benefit society when the inventor cannot otherwise prevent rivals from duplicating the gene more rapidly than she can. That is a problem for the small inventor. The large firm already has marketing power: Even without a patent, it likely can sell mass-produced copies of its gene and thus recover the costs of researching and developing it, before small rivals use its idea. Patents may also

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[2] Competition may induce minor innovations, at the expense of major inventions or discoveries, by encouraging thinkers to produce quickly. A protein chemist and Nobel laureate, Frederick Sanger, who sequenced amino acids in insulin, noted that his permanent research post, at the Medical Research Council in England, enabled him to focus on "more 'way out' and longer term" problems because he did not have to publish regularly. "I like the idea of doing something that nobody else is doing rather than racing to be the first to complete a project." (Quoted in Cook-Deegan, 1994, page 61.) On the other hand, cooperation may induce major discoveries by exploiting scale economies. The sequencing of the first chromosome from a cell with a nucleus involved 35 laboratories (Cook-Deegan, 1994, page 57).

help small firms more than large in protecting revenues from the invention. Without patents, small firms may fear price cuts by large rivals, which already enjoy falling marginal costs in producing genetic copies. These considerations suggest that patents for smaller inventors are more likely to help society than are patents for large firms.

Without patents, the small firm is more likely than large firms to forego inventing when it expects high costs. For example, compared to the small firm, a larger one may find it cheaper to finance invention, since it can draw upon richer retained earnings. Indeed, internal cash flow is important to small, new firms as they finance research (Scherer, 1999).[3] For example, a firm that mapped genes, Collaborative Research, could not raise $50 million on Wall Street; nor could it raise enough venture capital. It instead used internal funds (Cook-Deegan, 1994, pp. 41-42).

In project finance, the patent may thus help the small firm more than the large: The small inventor's ability to pledge a potential patent as collateral may make a lender more willing to finance her research, although the lender will not accept human capital as collateral.

Demand factors may also affect the efficiency of patenting. In particular, patenting may not misallocate many resources, compared to a world with no patents, when consumers long remain willing to pay for a costly invention. For, when creating a gene costs a lot, one of two cases may hold in a world without patents. Case A: A monopolist may invent because it expects to dominate the market. In such a case, a monopoly created by government, through patenting, need not be much worse for society than a monopoly that the market would have created without patenting. Case B: No firm invents without a patent, because none expects to dominate the market. In that case, the patent at least produces an invention.

The patent enables the firm to price to recover high costs. But the patent holder may be able to set the price higher than cost; and that may distort allocation if buyers are sensitive to price. A second condition for fairly efficient patenting, then, is that the demand for services from the gene does not grow price-elastic over the duration of the patent. In that event, adding a fee for the invention does not reduce demand severely. People would have bought almost as much had the price equaled just the marginal cost of duplication.

In short, patenting may induce small firms to embody existing ideas in products and processes that cost a lot to set up but that people are willing to pay a lot for.

Section II models a small firm that decides whether to research and develop, based on expected profits. Section III concludes with reflections.

II. Model

Consider the artificial gene as an innovation that improves the stream of services from a product with a market of $Q(t)$ unit sales at time t.[4] Examples of products that may embody such quality improvements may include farm products, such as firmer tomatoes as well as tobacco leaves that resist the tobacco mosaic virus; and health products, such

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[3] Scherer cites Charles P. Himmelfarb and Bruce C. Petersen, "R&D and internal finance: A panel study of small firms in high-technology industries," *Review of Economics and Statistics*, 76: 38-51, February 1994.

[4] The model extends to cost-cutting innovations as well as incorporates quality-improving innovations.

as an artificial hormone emulating an ovarian hormone that relaxes muscles during childbirth.[5]

Without the innovated gene, market profits are *Ï[t, Q(t)]*. Denoting the invention of the gene as *D*, let the increase in unit profits due to the gene be ã*[D]*.[6]

Potential operating profits for the inventor at time *t* are thus ã*[D] Q(t)*, if she indeed creates the gene. Before she starts work, however, she must settle two questions: How long to research and develop the gene; and whether she can expect to make money. If she can't expect to profit, she won't take on the project.

She sets a deadline of *T* for finishing R&D. Her choice of *T* depends on her expectation of R&D costs; it also depends on her funding, which may stem from equity, retained earnings, and loans. First consider retained earnings. Denote the small firm's share of market profits as *á(t*); denote the retained share of the firm's profits as *â(t)*. Let the current time be $t = 0$ and suppose that the firm entered the market at time $t = -T_e$. Let the discount rate be *r(t)*. Then the firm's retained earnings are

$$RE = \int_{-T_e}^{0} \beta(s)\alpha(s)\Pi[s, Q(s)]e^{-r(s)s}\, ds.$$

Larger retained earnings may help the firm borrow more and sell equity at a higher price. Both the bank and the equity owner may regard retained earnings as a measure of the firm's prudence and success. The size of the bank's loan at time *t* is thus a function of retained earnings as well as of time. Denote this loan function as *l[t, RE]*.

Denote the amount of initial equity sold as *e[0,RE]*. Under competitive conditions between equity holders and lenders, the firm will sell a dollar of equity at the same cost that it borrows a dollar.

Assume that the interest rate on the loan is fixed at the time that the loan is made, at rate $r(t) = r(0)$ for all relevant *t*. Then, at time *0*, the firm anticipates that it may borrow *l[0,RE]* and sell *e[0,RE]* equity at the price per dollar of *r(0)*. For simplicity, denote *l[0,RE] + e[0,RE]* as the sum *L[0, RE]*.[7]

As a one-project venture, the firm plans to pay off its loan and to effectively repurchase equity by the deadline *T* for completing its project. (The firm intends to declare bankruptcy if it embarks upon its project but does not complete it by *T*.)

Then, at time *0*, the firm anticipates that it may commit *RE + L[0, RE]* to R&D. Financial resources – retained earnings and loans -- must constrain the firm's expected costs of R&D, denoted as *C(t)*, as well as its costs of obtaining money. The firm thus seeks to satisfy

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[5] Schatz (1998), pp. 3-4.

[6] For example, Cetus Corporation licensed a technique that quickly produced DNA material, the polymerase chain reaction, to Hoffman-La Roche. In turn, Roche licensed it to university labs for a royalty as high as 9 percent (Cook-Deegan, 1994, pp. 76-77).

[7] As of the mid-1980s, biotechnological firms in Japan financed R&D through retained earnings and bank loans rather than through equity (Olson, 1986). In such cases, set *e[0,RE] = 0*.

Equation 1

$$\int_{-T_e}^{0} \alpha(s)\beta(s)\Pi[s,Q(s)]e^{-r(s)s}\,ds + L[0,RE] \geq \int_{0}^{T} e^{-r(s)s}\left(C(s)+r(0)L[0,RE]\right)ds + e^{-r(T)T}L[0,RE].$$

For simplicity, the analysis will assume the strict equality in the constraint.[8]

The firm picks T and $C(t)$ to maximize expected profits. If these are positive, then it proceeds with the project. The firm's expectations of profit hinge on its estimates of when – if ever -- it may finish the innovation. Denote the probability that the firm innovates at time t, given that it has not innovated before, as $Pr[D(t)|ND(t-\delta)]$. Here, δ is a small passage of time; and $ND(t-\delta)$ denotes that the firm has not innovated by time $t-\delta$.

An empirical study may indicate appropriate values for this probability. In a study of 16 firms in R&D, Edwin Mansfield and his students found that the probability that a research project would reach the point of development was 57 percent; that the probability of marketing the project, given that it was ready for development, was 65 percent; and that the project would make as much money as any other project, given that it had been marketed, was 74 percent. One may regard 57 percent as a tentative approximation to $Pr[D(T)|ND(T-\delta)]$: That is, at time 0, the researchers would estimate their chance of bringing the project to development by deadline T as 57 percent.

The work by Mansfield and others indicates that a firm's overall chance of achieving a project that would be as profitable as any other that it might attempt was the product of the three probabilities, or 27 percent.[9] This may provide an upper bound on the probability that the firm would not face rivalry that would destroy its profitable innovation. The paper will denote that probability as $Pr[NR(s)]$, where $s > t$ is the time needed for the project to earn the rate of return of the best alternative project.

Types of invention. Determinants of the probability depend upon the nature of the inventive work. Let us exclude invention that is purely random and instead consider two types of invention that may depend upon R&D spending.

The most familiar approach to invention in science is to try N known experiments with the expectation that one will lead to the desired result. For example, to identify the antibody for a given bacterium or virus, the researcher may try to reconstruct the protein that is the antibody. Suppose that she knows that the protein contains m particular amino acids; but she does not know their order. Then she may attempt $m!$ ordered combinations of the amino acids.[10] Such systematic experimentation is *passive invention*. Generally,

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[8] The assumption is not realistic. While the assumption may seem to suit the small firm that can afford to tackle only one project, the analysis also assumes that the firm is risk-neutral, which seems unlikely for the one-project firm.

[9] Edwin Mansfield *et al.*, *Production and application of new industrial technology*, New York: W. W. Norton, 1977. I draw upon the summary of the study in F. M. Scherer, *New perspectives on economic growth and technological innovation.* Washington, D. C.: Brookings Institution, 1999.

[10] As another example, the researcher may wish to determine the sequence of nucleic acid bases in a segment of DNA. She may use radioactive tags to mark each of the four bases in DNA segments. She may then run four experiments, each focusing on where a particular base occurs in the initial stretch of DNA. Each experiment may split the stretch at the point where the base occurs. These splits produce several small segments. The researcher may sort the resulting segments by weight. A base that occurs toward the start of the initial stretch of DNA would be associated with lighter segments. A base that occurs

the researcher envisions a field of known or guessable dimensions, which she now seeks to cover in pursuit of a quarry of an invention. The process of invention itself is thus routine, or passive.

Without more information, the researcher may well reason that the probability of passive invention increases in the share of the "field of experiments" that has already been covered. Suppose that the researcher anticipates that, of *N* experiments, each is equally probable to yield her the desired result. At time *s*, she tries *n(s)* experiments. Then she may conceive that

$$\Pr[D(t) \mid ND] = \frac{\int_0^t n(s)\, ds}{N}.$$

The researcher may increase the conditional probability of invention at time *t* by trying more experiments *n(s)* for any $s \leq t$. Thus *Pr[D(t)|ND]* increases in the level of spending *C(t)*.

A less familiar form of invention is closer to art than to science. Whether or not the researcher conceives of certain dimensions to her field of experiments, she may believe that following an intuition or instinct will improve her conditional probability of invention at time *t*. For example, she may have in mind an image that serves one of two purposes. The image may directly represent the object that she wants to invent, such as a more durable tire for a mountain vehicle. Or it may provide a metaphor for the process that she wants to invent. Examples include a mass production line that sequences specialized tasks, thus providing a blueprint for a more rapid method of genetic cloning; or a solar system as a metaphor for a viral molecule or system. Creating the image – or, more generally, creating the instinct that it embodies – may depend on the motivating force, such as a sense of excitement; in turn, the excitement may be generated by an increase in the rate of spending. Thus, in such *active invention*, the probability of discovery, *Pr[D(t)|ND]*, may increase in the rate of spending, *dC/dt*, rather than in the level of spending *C(t)*. The researcher conceives that, in effect, the insight itself completes the invention; that developing it into a useful product is a low-cost routine.[11]

In sum, active invention provides hypotheses; passive invention tests them.

Genetic engineering offers examples of both passive and active invention, sometimes in the same line of experiments. In an active invention of 1956, Arthur Kornberg had an insight into how to show that nucleic acid bases link and replicate. To a test tube, he added natural DNA, from a colon bacillus. The test tube already contained the four bases as well as such nutrients as magnesium, inorganic salts, and an enzyme for building DNA. By contrast, in a passive invention, he verified that replication normally required all four bases. His approach was to repeat an experiment, each time omitting one or more nucleotides from a test tube, to see whether the cells would replicate (Beadle

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only toward the end of the DNA stretch would be associated with heavier segments. The researcher may thus determine the sequence of bases in DNA.

[11] The analysis also extends to a third type of invention that blends passive and active invention. In this approach, the researcher plans to repeat a type of experiment for an unknown number of times. She is not sure that some maximum number of experiments would deliver the desired result, so she plans to experiment until she succeeds. We may characterize this type of invention as *passive unlimited*.

and Beadle, 1966). The dimensions of this field of experiments were known: No more than 4! combinations of nucleotides would seem possible.

It is hard to determine which of the two approaches toward invention – passive or unlimited -- may be the more important in genetic engineering. A famous invention in the field – the double-helix model of DNA designed by James Watson and Francis Crick -- was an active invention (Watson, 1968).[12] This paper, however, will focus on passive invention. It is easier to analyze, and it seems likely to consume more resources, than active invention.

The probability of nonrivalry. When the small passive inventor repeats experiments in a routine, she faces the danger that a larger rival will finish the project first. That is, the large firm may learn which experiments failed for the small inventor and then use its own superior facilities to do the rest of the experiments quickly. The analysis assumes that, in this event, the small firm's future profits from the invention will go to zero.

Turn, then, to the probability that no rival innovates before the small firm by time t. Denote this probability as $Pr[NR(t)]$. It is higher if all firms in the market find that producing a little more will cost them a lot more. Such diseconomies of scale prevent the rise of any one firm so large that it could have the resources to quickly reproduce the small firm's invention. In short, $Pr[NR(t)]$ increases in the second derivative of the market function that expresses the total operating cost of producing Q units at time t. Denote this cost function as $K[Q(t)]$. Higher values for $\partial^2 K/\partial Q^2$ – the rate of change in marginal cost -- suggest that the small firm is less likely to face large rivals that, through declining marginal costs, have accumulated large profits to finance R&D.

Also, $Pr[NR(t)]$ is smaller when the small firm has spent more on R&D up to time t. When the small firm has done more of the work, less remains to the informed large rival to complete in order to reproduce the invention. Once the small firm has completed the invention, however, $Pr[NR(t)]$ may depend on the amount of time needed to reverse-engineer it.

With a patent, the small firm can prevent reverse engineering by threatening a lawsuit. Assume that, in a world with patents, $Pr[NR(s)] = 0$ for $s > t$, where t is the time of invention.

The small firm's decision. In sum, the small firm will undertake R&D if it does not expect negative profits – that is, if $\Pi^e \geq 0$, or[13]

Equation 2

$$\int_0^T \Pr[D(t) \mid ND] e^{-r(t)t} \int_t^\infty \Pr[NR(s)] e^{-r(s)s} g[D(t)] Q(s)\, ds\, dt \geq \int_0^T \left(1 - \Pr[D(t) \mid ND]\right) e^{-r(t)t} C(t)\, dt.$$

[12] As another example, a chemist and Nobel laureate, Kary Mullis, conceived of the polymerase chain reaction while driving through the redwoods of California, to a weekend cabin (Cook-Deegan, 1994, page 72).

[13] In Equation (2), the first exponential term applies to the time period $[0,t]$; the second exponential term applies to the time period (t,∞). Note that if invention occurs at time t satisfying $0 \leq t \leq T$, then the probability of discovery in future moments goes to zero: $Pr[D(v);.] = 0$ for $v > t$.

Choosing T. A first-order condition suggests that the firm will pick *T*, if positive, to equate marginal expected profits to marginal expected costs:

$$\Pr[D(T) \mid ND] \int_T^{\infty} \Pr[NR(s)] e^{-r(s)s} g[D(T)] Q(s)\, ds = \big(1 - \Pr[D(T) \mid ND]\big) C(T).$$

Rearrangement of the condition suggests that, if the firm expects positive net profits, then it will plan to extend R&D (if necessary) up to a time *T* when the probability of discovery is slim, holding constant the impact of the discovery time on the profit markup ã:

Equation 3

$$\frac{\int_T^{\infty} \Pr[NR(s)] e^{-r(s)s} g[D(T)] Q(s)\, ds}{C(T)} = \frac{1 - \Pr[D(T) \mid ND]}{\Pr[D(T) \mid ND]}.$$

One may interpret the left-hand side of the condition in (3) as the optimal rate of return to last-minute spending on R&D.

Sufficiency. Merely satisfying this condition does not ensure that the small firm will maximize net profits. But satisfying both first-order conditions – for choosing *T* and *C(t)* – does ensure a unique maximum of expected profits when the determinant for the full second-order condition is everywhere positive.

Now consider the components of the full second-order condition. Consider first the partial second-order condition with respect to *T*. It is:

Equation 4

$$\begin{aligned}
\frac{\partial^2 \Pi^e}{\partial T^2} &= \frac{\partial \Pr[D(T) \mid ND]}{\partial T} \int_T^{\infty} \Pr[NR(s)] e^{-r(s)s} g[D(T)] Q(s)\, ds \\
&- \Pr[D(T) \mid ND] \Pr[NR(T)] e^{-r(T)T} g[D(T)] Q(T) \\
&+ \Pr[D(T) \mid ND] \int_T^{\infty} \Pr[NR(s)] e^{-r(s)s} \frac{\partial g[D(T)]}{\partial T} Q(s)\, ds \\
&- \big(1 - \Pr[D(T) \mid ND]\big) \frac{\partial C(T)}{\partial T} \\
&+ \frac{\partial \Pr[D(T) \mid ND]}{\partial T} C(T).
\end{aligned}$$

Of the five terms on the right-hand side of the second-order condition, the signs of the first, second and fifth are clear (positive, negative and positive, respectively).[14] In contrast, the signs of the third and fourth terms may depend on the circumstances of the

[14] Under passive invention, $dPr[D(T)]/dT > 0$ since the firm can only improve its chances of discovery by taking the time to do another experiment.

case. One may conjecture that the second-order condition is more likely to be negative when the firm undertakes an invention that is most valuable per unit when it is applied immediately, such as a vaccine for AIDS. For, if the value of the invention is highest at the moment of invention – even if invention occurs right in the last moment *T* of the R&D program -- then that value will fall in the future [$d\tilde{a}/dt < 0$]; this will render negative the third term.

The second-order condition is also more likely to be negative when the small firm senses rivalry toward the end of its R&D program; for it will then spend more rapidly toward time *T* [$dC(T)/dT > 0$], thus ensuring that the fourth term is negative. The last assumption may fit Scherer's observation that firms often spend on R&D along a bell-shaped curve over time: They spend little early in the program, when they focus on whether the project is feasible; spend more in middle stages on pilot projects; and then wind down spending (Scherer, 1999). The R&D program considered in this paper ends with the completion of a successful pilot project.

In sum, planning to lengthen the project until the moment *T* when expected profit equals expected cost, at the margin, is more likely to maximize expected profits when the small firm undertakes a project of immediate value amid keen rivalry.

Choosing C(t). After selecting *T*, the passive inventor chooses the level of spending at each moment, *C(t)*, to maximize expected profits. During the R&D program, her higher level of spending may also increase the chances that a larger rival will complete the project before she does. Thus, for $0 \leq t \leq T$, *Pr[NR(t)]* may decrease as *C(t)* increases.

Summed over the time period *T*, the static problem yields, for an interior solution of *C(t)*, the first-order condition

Equation 5

$$\int_0^T \frac{\partial \Pr[D(t); C(t) \mid ND]}{\partial C(t)} e^{-r(t)t} \int_t^\infty \Pr[NR(s); C(t)] e^{-r(s)s} g[D(t)] Q(s)\, ds\, dt$$
$$+ \int_0^T \Pr[D(t)] e^{-r(t)t} \frac{\partial \Pr[NR]}{\partial C(t)} g[D(t)] Q(t)\, dt$$
$$= \int_0^T (1 - \Pr[D(t)]) e^{-r(t)t}\, dt.$$

Throughout the project, the inventor plans to spend at each moment until the concurrent increase in expected profits equals the probability of no discovery at that moment. The intuition is this: The momentary increase in expected profits is the marginal value of spending another dollar on research at time *t*. The marginal cost is the expected foregone value of spending the dollar on another purpose. That expected foregone value is $1 times the probability that the dollar would not have completed the invention. Summing the momentary conditions yields the condition above, in (5).

Full sufficiency. To consider the full sufficiency condition, one must first characterize the cross-partial of the expected profit function with respect to the two choice variables: The R&D cost function *C(t)*; and the time horizon *T*, which affects

profits via the cost function. Since the budget constraint binds for the firm, extending the duration of the R&D project will not increase its rate of spending:

$$\frac{\partial^2 C}{\partial t \partial T} \leq 0.$$

This suggests that spending the given amount of money over a longer period will lower the amount spent at each moment – and thus moderate the reduction of expected profits:[15]

Equation 6

$$\frac{\partial^2 \Pi^e}{\partial T \partial C(t)} \leq 0.$$

If this cross-partial is not strongly positive, then the sufficiency condition depends only on $d^2Ð^e/dT^2$, in (2), and on

Equation 7

$$\frac{\partial^2 \Pi^e}{\partial C(t)^2} = \int_0^T \frac{\partial^2 \Pr[D(t); C(t)]}{\partial C(t)^2} e^{-r(t)t} \int_t^\infty \Pr[NR; C(t)] e^{-r(s)s} g[D(t)] Q(s)\, ds\, dt$$
$$+ \int_0^T \Pr[D(t); C(t)] e^{-r(t)t} \frac{\partial^2 \Pr[NR; C(t)]}{\partial C(t)^2} g[D(t)] Q(t)\, dt < 0.$$

The sign of this second derivative, in (7), assumes negativity of the second partials of both probability functions – *Pr[D(t);.]* and *Pr[NR;.]* -- with respect to spending at each moment *t*. That is, at a given moment, an additional dollar of spending by the small firm becomes increasingly more useful to the large rival than to the small firm itself, perhaps because the large firm has the facilities to quickly take advantage of a near-complete project.

These considerations suggest that satisfying the first-order conditions for choosing *T* and *C(t)* are most likely to ensure maximization of expected profits if the small firm thinks that it is under the gun to finish a project that would have its greatest value in the near future. The first-order conditions are thus most likely to provide "rules of thumb" in the cases of pressing competition that are, in fact, of the greatest policy concern.

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[15] The sign of the derivative in (6) permits the possibility: A lower level of R&D spending could make less probable that a larger rival would finish first by so much as to boost the profits expected by the small inventor. For example, the larger firm may have superior facilities for gathering intelligence about rivals, so that it learns a lot (surreptitiously) when the small inventor spends a lot. In that case, the small firm may prefer to spend less and thus to transmit less information to her rival.

Lease value of invention. Having described the small firm and its decisions, we may now further specify the function that gives the value of its patent lease, $g[D(t)]$. A firm with more experience in the market is more likely to come up with a valuable idea to patent. Thus the expected value of the patent may relate positively to the sales that the firm has accumulated up to the time that it would begin its research project:

Equation 8

$$g[D(t)] = f\left[\int_{-T_e}^{0} \alpha(s)Q(s)\, ds\right].$$

Here, *D(t)* is a binary variable that expresses whether the invention was developed at time *t*.[16]

Optimal invention. Define a "socially optimal invention" as one that would yield positive net profits *ex post*. Until rivals learn how to make the new product, the inventor may charge a net price that reflects its marginal social value, net of cost. *Ex post* profits seem a better indicator than *ex ante* profits of how the product would affect actual social welfare.

For simplicity, the analysis assumes that the invention would be worth the same in every use, so that $\tilde{a}(t)$ reflects the full value at time *t* of the invention to any user. The inventor thus may capture the total surplus of the invention. While not realistic, the assumption may not be outrageous: The use value of an artificial gene, broadly defined, may be so universal that it is the same for all users.

Viewed from time 0, it is socially optimal to undertake the R&D project if *ex post* profits are not negative – that is, if

Equation 9

$$\int_{t}^{\infty} g[D(t)]Q(s)e^{-r(s)s}\, ds \geq \int_{0}^{t} C(s)e^{-r(s)s}\, ds.$$

Comparing (9) to the first-order condition to choose *C(t)* for the R&D project, in (3), suggests that the small inventor may sometimes refuse a project that is socially optimal. For simplicity, assume that *Pr[NR(s); C(t)]* is a constant with respect to time; and that the discount rate *r(t)* is 0 for all *t*. Then, from (3) and (9), the small inventor will decline a socially optimal project when, for all *t* that satisfies $0 \leq t \leq T$,

[16] For simplicity, the expression in (8) assumes that the small firm's share of sales equals its share of profits. If the small firm operates at a higher cost than rivals, then the profit share will understate the sales share.

Equation 10

$$\int_0^t C(v)\,dv << \frac{1-\Pr[D(t);C(t)\mid ND]\left(1+\dfrac{\partial \Pr[NR]}{\partial C(t)}g[D(t)]Q(t)\right)}{\Pr[NR(s);C(t)]\dfrac{\partial \Pr[D(t);C(t)\mid ND]}{\partial C(t)}}.$$

This condition is more likely to hold when, essentially, more spending by the inventor would help her rival more than herself. In particular, the small inventor is more likely to pass up a project that is socially optimal under several conditions:

First, her probability of discovery is low. That is, *Pr[D(t);.]* is small, so that the right-hand side of the inequality is relatively large and thus is more likely to exceed a given total R&D cost (expressed on the left-hand side of (10)).

Second, spending more would spark rivalry that strips the inventor of high profits, early in marketing. That is, the term

$$\frac{\partial \Pr[NR]}{\partial C(t)}g[D(t)]Q(t)$$

is large in absolute value. The term is negative: By spending more, the inventor would make more likely that the rival would finish the innovation first; it thus becomes less likely that no rivalry would occur (*dPr[NR]/dC(t) < 0*). If this term is large in absolute value, then it will connote a large numerator in (10), since the term multiplies with another negative term, *-Pr[D(t);.]*.

Finally, higher spending does not make discovery much more likely. That is, the derivative

$$\frac{\partial \Pr[D(t);C(t)\mid ND]}{\partial C(t)}$$

is small.

Spillovers. Generally, (10) describes when the profit-minded inventor would decline an R&D project that would have made money had it been completed. One specification of (9) and (10) suggests that the small inventor may especially pass up projects with large spillover benefits, such as dispelling a communicable disease. For a population of size P, denote the social value of an innovation that mitigates a communicable disease as *V[t, P(t), Q(t)]*. Here, *V* has positive first partial derivatives; a positive cross-partial; and negative second derivatives. Then the invention would add net value if

$$\int_t^\infty \left(g[D(t)+V[s,P(s),1]\right)Q(s)e^{-r(s)s}\,ds \geq \int_0^t C(s)e^{-r(s)s}\,ds.$$

The inventor, however, might disregard *V[.]* since she would receive no rent on it.

Falling short of optimality. Denote Equation (10) as a *condition for suboptimality*, and consider a special case of it, for patenting. The patent would protect the small inventor against her larger rival after she innovates. For simplicity, assume a perpetual patent. It would connote that

$$\Pr[NR(s); C(t)] = 1$$

and subsequently that

$$\frac{\partial \Pr[NR(s); C(t)]}{\partial C(t)} = 0$$

for all $s \geq t$, where t is the time of innovation. These changes render the condition for suboptimality in (10) as

Equation 11

$$\frac{1 - \Pr[D(t); C(t) \mid ND]}{\dfrac{\partial \Pr[D(t); C(t) \mid ND]}{\partial C(t)}} >> \int_0^t C(s)\, ds.$$

Rewriting (11) in terms of the elasticity of the probability of invention with respect to spending, å, yields

$$\frac{C(t)}{\varepsilon}\left[\frac{1 - \Pr[D(t); C(t) \mid ND}{\Pr[D(t); C(t) \mid ND]}\right] >> \int_0^t C(s)\, ds,$$

where

$$\varepsilon = \frac{\partial \Pr[D(t)]}{\partial C(t)} \frac{C(t)}{\Pr[D(t)]}.$$

Even with patenting, the small inventor might well pass up a project of social value if invention is unlikely (*Pr[D(t)]* is small); if spending relatively more does not increase the probability of invention by relatively more (å is small); and if the project would cost a lot even at the brink of invention (*C(t)* is large).

These results assume that the small inventor does not cooperate with the large firm in research. A Cournotian analysis, however, has shown this: Two firms that cooperate on research will produce cost-cutting innovations that come closer to the social optimum than a competitive market would produce, when the innovations create large spillovers for the firms.[17]

[17] d'Aspremont and Jacquemin (1988).

Specifications

The probability that the small firm will complete its invention in moment *t*, given that it has not done so before then, may follow the form of a Poisson function (Feller, 1968):

Equation 12

$$\frac{\lambda e^{-\lambda}}{1-e^{-kt}\,\lambda t},$$

Here, *ë* expresses the probability of an invention at a given moment, and it may rise as the researcher spends more or devotes more time to her project: *ë = ë[C(t), t]*. One may loosely interpret (12) in this way: The numerator gives the probability that the small firm completes its invention in moment *t*. ë is the probability that the invention occurs in a small subunit of moment *t*, and $e^{-ë}$ is the probability that no invention occurs in the other subunits of that moment. The denominator gives the probability that no invention occurs up to time *t* – that is, 1 minus the probability that the invention does occur at some time up through *t*. The specification assumes that the probability of an invention at any moment is independent of the probability at any other moment.

The suitability of the Poisson specification is suggested by the non-negativity of the first-order derivatives:

$$\frac{\partial PR[D(T)\mid ND]}{\partial T}=\frac{e^{-\lambda}\,\frac{\partial \lambda}{\partial T}\left[1-\lambda^{2}\right]}{1-e^{-\lambda T}\,\lambda T}+\frac{\lambda e^{-2\lambda T}}{\left[1-e^{-\lambda T}\,\lambda T\right]^{2}}\left[\frac{\partial \lambda}{\partial T}T+\lambda\right]\left[1-(\lambda T)^{2}\right]\geq 0$$

where one chooses time units so that $T \equiv \lambda$; and

$$\frac{\partial PR[D(t)\mid ND]}{\partial C(t)}=\frac{\frac{\partial \lambda}{\partial C}e^{-\lambda}\left[1-\lambda^{2}\right]}{1-e^{-\lambda t}\,\lambda t}+\frac{e^{-\lambda t}\,\frac{\partial \lambda}{\partial C}t\left[1-\lambda^{2}t\right]}{\left[1-e^{-\lambda t}\,\lambda t\right]^{2}}\geq 0$$

III. Conclusions and reflections

Patenting may accelerate genetic research when small inventors face both high development costs and large rivals that produce with a nonconvex technology. In that case, genetic patents may particularly encourage small firms to do cancer research that focuses on small particles and that would produce genes to be cloned. Without a

prospective patent to secure funding, the small firm may not be able to afford research into small particles, which requires special microscopes. This is particularly the case since the small firm must try to complete its project quickly, for otherwise a large rival might beat it to the punch. The small firm is likely to have a large rival because cloning, as a production technology, probably enjoys scale economies.

In principle, the patent may enable the inventor to charge a price so high that it blocks some trades. But one may speculate that the problem would not be serious for genetic research into cancer. For this service, demand seems likely to grow more price-inelastic over time. In particular, the share of health costs in spending per capita in the U.S. has been rising over time: This suggests that aversion to risks that threaten life may rise with annual income, perhaps partly because the opportunity cost of the risk rises with income. Moreover, an insurer pays the bill, so the consumer may not worry much about the price of the research.

These considerations suggest that granting powerful patents for cancer research may be somewhat efficient. Not even a perpetual patent, however, would induce the small inventor to attempt all valuable inventions, since a large rival may finish the work that the small inventor begins – particularly if research advances cost much.

One way to increase the market power of the small inventor is to lengthen her patent. But would a long patent on a genetic invention serve consumers? That may depend in part on whether the physical capital used in research imposes high fixed costs. One may expect that, as research tools improve, enabling the study of smaller particles, the granting of longer patents would encourage research with longer-run benefits.

A longer patent would confer market power on the inventor for longer. One may speculate, however, that this luxury of time may induce the inventor to contract with the one producer that, over the long run, proves to be the most reliable for her. The grant of a long-term patent may thus create market power for both the inventor and the producer. The cloning firm can enjoy declining marginal costs by inserting gene-containing bacterial plasmids into mammalian cells. The cells then multiply in large tanks, presumably at low cost. A lease on an artificial gene may enable the producer to quickly lock up its market by expanding at falling marginal cost.

How might the government best grant market power to inventor and producer? Suppose that the producer's technology is nonconvex. Imagine a competitive equilibrium for this production: Firms maximize profits, consumers maximize utility, and markets clear. The equilibrium may not be Pareto-optimal, since the nonconvex firm may not produce all that has net value. To minimize cost, it may use just one production process, specializing in a few inputs – and ignore more costly processes that use other inputs. If the unused inputs are not mobile, they will go to waste. For example, the use of hardy genetic hybrids in agriculture may lead farms to substitute soil for labor. The farms could grow more food by using both inputs, but that might not minimize the cost of producing a given amount of food.

Suppose that, at given prices, the government can design a policy, of tax-financed subsidies, that enables the nonconvex producer to break even while producing a mandated amount that satisfies the three conditions of the politico-economic equilibrium: profit and utility maximization as well as market clearing. Such an equilibrium, if it exists, is Pareto-optimal (Laffont, 1988). Might that equilibrium exist for the nonconvex

producer of artificial genes? Is it preferable, for political or other reasons, to have a patenting policy that subsidizes production rather than modifies prices?

Longer-run questions may bear on philosophy rather than policy. Might the patenting of genes reach a point – such as the patenting of a genome – that confers ownership of a life or species? While speculative, the question may be practical, since the genome may be founded on a subadditive cost function for producing polypeptide chains. Cost minimization may naturally lead protein producers from genes to genomes.

The Supreme Court ruled in 1980, in *Diamond v. Chakrabarty,* that inventors could patent genetic innovations, such as artificial bacteria that decompose crude oil, because these derive from human hands rather than from nature (McCuen 1985). One may ask whether the human creation of an entire genome would amount to creation of an animal species; and whether one would be more likely to view that creation as immoral if the genome is more complex.[18]

Beyond that, one may ask whether the creation of an entire human genome would qualify as a human invention that one can patent and own -- or as a life that cannot be owned, regardless of its origins, under the Thirteenth Amendment.

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[18] If the last issue matters, then one would like to know how to define the complexity of a genome. For example, the nematode *C. elegans* has a third more genes than the fruit fly *Drosophila*; but its genome -- measured in the number of pairs of nucleic acid bases – is only half as large. If the number of genes is the standard, then one is struck that *C. elegans* has almost five times as many genes as the *E. coli* bacterium and only a fifth as many as the human (Cooper 2000, page 145. One would not easily accept the hypothesis of linear complexity for these three species.

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