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PART TWO: Industry Issues

7. The Source of Comparative Advantage in the Biotechnology Industry: A Real Options Approach

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The Source of Comparative Advantage in the Biotechnology Industry: A Real Options Approach

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Chapter 7

The Source of Comparative Advantage in the Biotechnology Industry: A Real Options Approach

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Introduction

Commercial biotechnology has been and continues to be the nearly exclusive province of US enterprise. From the late 1970s to the present, biotechnology research and production has concentrated in the US, rather than in other industrialized regions such as Western Europe. Casual inspection of industry data confirms that the early US dominance in biotechnology has been perpetuated over time. In 1996, US biotechnology firms numbered 1,287 and employed 118,000 workers, compared to 716 firms and 27,500 workers in Europe. US firms earned $14.6 billion in revenues, far exceeding the European total of $1.4 billion. Significantly, US biotechnology firms spent $7.9 billion on research and development (R&D); European firms spent only $1.2 billion (Ernst & Young 1997a, 1997b).

This evidence suggests that the US holds a comparative advantage in the biotechnology industry, *vis-à-vis* other Northern countries. Basic principles of international trade hold that comparative advantage is derived from the presence of some form of heterogeneity in the international economy. Trade models used to characterize the pattern of specialization and trade in high technology industries, often ascribe the source of heterogeneity either to the presence of international differences in inherited resource endowments, such as skilled labor or capital, or national pools of knowledge (Grossman and Helpman 1991).

These models do not provide a compelling explanation for the current pattern of specialization in biotechnology, since their assumptions do not accord with empirical descriptions of the Northern trading community in general, or the biotechnology industry in particular. The post-1945 period has witnessed a convergence among industrialized countries by most measures, especially in regard to traditional sources of comparative advantage such as relative factor composition. In addition, there is no evidence that any nation enjoyed the advantage of a larger initial national stock of knowledge which lowered per-unit R&D costs for domestic firms.

Establishing the pattern of specialization and trade in biotechnology requires the elucidation of alternative sources of heterogeneity which can account for the emergence of the US as the world leader in this industry. An examination of a set of stylized facts characterizing R&D investment in the biotechnology industry suggests that the US comparative advantage in biotechnology relative to other Northern countries can be

explained through sources of heterogeneity within the R&D investment process. If biotechnology R&D is analyzed in terms of the optimal management of a real option, it illustrates how the presence of sources of heterogeneity within the R&D process can generate asymmetric investment behavior across countries. In turn this may be sufficient to explain the US comparative advantage in biotechnology. This suggests that comparative advantage can be established without appealing to the uncorroborated assumption of international differences in inherited resource endowments.

In this chapter, sources of heterogeneity within the R&D investment process are proposed as a plausible explanation for the US comparative advantage in biotechnology. In section 2, a set of stylized facts is listed that characterize biotechnology R&D investment, and two candidate sources of heterogeneity that impact R&D investment are identified: the per-period rate of investment and the level of uncertainty pertaining to the domestic regulatory regime. In section 3, a model of biotechnology R&D investment is developed, based on an extension of Pindyck's (1993) real options model of irreversible investment with uncertain cost. The implications of this model for the issue of comparative advantage in the biotechnology industry are examined in sections 4 and 5. The chapter is summarized in section 6.

Stylized Facts of Biotechnology R&D

To understand how firms in one country can ultimately dominate an R&D-intensive industry such as biotechnology, a promising avenue of inquiry is the actual process of R&D investment itself. An examination of this process in the biotechnology industry yields the following stylized facts, summarizing its salient features:

1) biotechnology R&D programs are lengthy, typically extending over multiple years
2) time to build for an R&D program is unknown *a priori*
3) cost to completion is subject to ongoing uncertainty from a number of sources:
    - the physical difficulty of completing the R&D
    - the external investment environment
    - the scientific environment
4) R&D costs are made upfront and are at least partially irreversible.

These stylized facts characterize biotechnology R&D as a lengthy process, where firms must make substantial resource commitments in the face of little or no offsetting cash flow. While biotechnology companies that choose to leave the industry can occasionally sell their research to other firms, R&D that has been shown to be unprofitable for one firm will likely be unprofitable for another. It is difficult, therefore, to recover costs from past R&D, and these expenditures must be considered at least partially sunk.

The three sources of uncertainty outlined above warrant further explanation. As Pindyck notes, at the time an R&D program is initiated, limited information is available

regarding the effort, resources and time required to realize successfully the future payoff. Initiating the project and completing successive stages will incrementally reveal information related to these issues. As the investment proceeds, the barriers to completion may become higher or lower, but the true cost of the investment is only known with certainty when the project is completed. In the presence of this form of uncertainty, which Pindyck labels *technical uncertainty*, investment contributes not only toward the completion of the project, but also toward the resolution of the project's final cost. This "information revealing" product of investment enhances the incentives for the firm to commence the R&D project immediately.

The second form of uncertainty arises from factors external to the actual R&D process which may impact the cost of investment. For example, the regulatory regime governing R&D in the industry, or the current status of intellectual property rights. Regulatory uncertainty may arise from unpredictable aspects of the rules governing the commercialization of biotechnology products, in the form of unpredictable compliance costs incurred over the course of the R&D process. The level of these costs may be higher or lower depending on how regulators respond to factors such as public opinion or safety concerns. In contrast to technical uncertainty, information about external factors such as the regulatory regime may be observed regardless of whether or not the firm is investing. This tends to have a dampening effect on investment incentives, since the firm may benefit from delaying investment in order to observe these external factors and thereby obtain more information about their future trajectory.

Finally, uncertainty associated with the scientific environment may take the form of new discoveries stemming from basic research, which then impact firms' perception of the technological or scientific feasibility of their R&D. In biotechnology, basic research may reveal that some or all of the scientific assumptions upon which the R&D rests are in error. An illustrative case is the effort to develop a drug therapy for sepsis, an infection often encountered in cancer patients or burn victims. Numerous biotechnology companies collectively invested hundreds of millions of dollars in R&D directed at developing a drug for sepsis. However, all of the drugs failed, because it was later discovered that sepsis could not be easily treated with only one drug. The fact that much of R&D in biotechnology is based on incompletely understood living systems such as humans, animals, and plants implies that R&D programs are subject to drastic changes in their costs, risks, and ultimately, their prospects for success as new scientific knowledge is accumulated.

The stylized facts presented above summarize the prominent features of R&D investment in the biotechnology industry. More specifically, they collectively describe the process undertaken by firms engaged in the *commercialization* of biotechnology. Trefler (1993: 980) observes that,

> "[o]ne facet of national differences … is the ability to commercialize technology. While basic research is internationally available through publications of the scientific community, the translation of basic research

> into low-cost production processes is both a guarded secret of firms and the comparative advantage of the developed countries."

Trefler's observation can be extended to the idea that the ability to commercialize technology is also a comparative advantage of some developed countries over other developed countries, as in the case of the US and biotechnology.

A country's comparative advantage in commercializing new technologies can be thought of as the ability to innovate more rapidly than rival countries. The stylized facts listed above suggest at least two candidate sources of heterogeneity pertinent to this issue. First, since biotechnology R&D is lengthy, the rate at which a firm can invest will have important implications for average time to build, or equivalently, the rate of innovation. Secondly, the presence of regulatory uncertainty and its implications for investment incentives suggests that a reduction in the level of uncertainty surrounding the regulatory regime will reduce the incentive for firms to delay investment in order to obtain more information about the future path of the regulatory environment.

Evidence supports the contention that these sources of heterogeneity in fact are relevant to a comparison of the biotechnology industries in the US and Europe. *The Economist* (1996a: 21) observes,

> "In America, companies such as Netscape and Genentech have sprung up to lead the Internet or biotechnology even before such things can really be classified as industries. By contrast Europe's leaders often tend to be big companies stuck in 'sunset' industries such as chemicals or cement."

This disparity between the US and Europe may be in part attributable to the fact that European firms face more difficulties in obtaining investment capital. *The Economist* (1996b: 89) notes,

> "... [Europe] seemingly has no shortage of venture capital, but most of it has been going into relatively unadventurous investments … only a fraction has been invested in start-ups."

In contrast, the US has a well-tested mechanism for channeling funds to risky high technology enterprises, notably the NASDAQ equity market.

Heterogeneity between the US and Europe also exists in the guise of domestic regulatory regimes, especially in terms of the relative ease with which biotechnology products can gain approval for release by national regulatory agencies. In Europe, product approval is a much more costly and uncertain prospect than in the US. For example, in 1992, the US Food and Drug Administration determined that genetically engineered foods would only have to satisfy the same health and safety standards imposed on naturally occurring foods. In contrast, European biotechnology firms face a protracted approval process, fraught with uncertainty. *The Economist* (1998: 80) notes that the European regulatory regime,

> "is hardly providing encouragement to Europe's GMO [genetically modified organism] industry."

It is reasonable to hypothesize, therefore, that the US biotechnology industry possesses certain advantages, present within the R&D process, that have allowed it to move ahead of its rivals through more rapid innovation, independent of any international differences in inherited resource endowments such as factor stocks.

A Real Options Model of Biotechnology R&D Investment

In order to investigate the hypothesis stated above, a model of biotechnology R&D investment is needed. The real options approach to investment is well suited for analyzing the R&D investment decision faced by biotechnology firms. Real options investment models are based on three observed characteristics of investment: it is at least partially irreversible; it is subject to ongoing uncertainty; and the timing of the investment is at the discretion of the firm. Taking these characteristics into account, the opportunity to invest is likened to holding a financial option, except that the option is "written" on a real asset, rather than a financial instrument. The firm holds the right, but not the obligation, to initiate investment. When a firm invests, it irrevocably "kills" the option to delay, and, therefore, the value of this lost flexibility must be included in the cost of investment. As a result, the return necessary to persuade a firm to invest will tend to exceed the direct cost of capital, contrary to the traditional net present value (NPV) investment model.

This approach suggests a need for an investment rule that calls for investment to be initiated when exercising the option to invest is profitable. Methods for pricing financial options can be adopted for this purpose. It can be shown that investment strategies – i.e., decision rules for exercising the option, and for abandoning the project midstream – are heavily influenced by several factors. For example, the necessity to invest incrementally, the presence of time to build, the degree and type of uncertainty, and the rate of productive investment. Significantly, these factors coincide with the list of stylized facts describing the structure of R&D investment in the biotechnology industry. Therefore, real options investment models can accurately represent the features of biotechnology R&D that are neglected in the NPV investment model.

In a real options framework, a biotechnology firm's investment strategy may be described as follows. Consider a biotechnology firm that acquires an opportunity - i.e., an option - to invest in an R&D program. The firm can either invest right away - i.e., exercise the option - if current investment conditions warrant, or alternatively, it can continue to hold the option while at the same time observing the evolution of investment conditions over time. Should conditions change such that investing becomes feasible from an economic perspective, the firm will then exercise its option to invest at that time.

Suppose the firm does invest, either right away or at a later date. Then, as the stylized facts indicate, the firm invests in the R&D program incrementally, extending the

investment over multiple time periods. As the firm invests, the stochastic conditions surrounding the investment continue to fluctuate. As noted in the stylized facts, stochastic elements arise from the physical difficulty of completing the investment, external factors impacting the investment such as uncertainty over the domestic biotechnology regulatory regime, or the results of basic research conducted by the scientific community. All of these factors may combine to make the R&D proceed faster or slower than anticipated. There is a possibility that conditions may deteriorate to the point that the investment becomes economically untenable. In other words, the resources required to complete the R&D may grow to such a level that the firm's optimal strategy is to cut its losses at the level of sunk costs expended to date and terminate the R&D midstream. Alternatively, a *termination event* could occur – an event that renders the R&D program immediately worthless. For example, new results from the scientific community may indicate that the R&D is being conducted under erroneous assumptions, and it is, therefore, useless to proceed further.

Given this scenario, how does the firm manage its option to invest, and once investment is initiated, its (reverse) option to abandon the project midstream should conditions take a turn for the worse? As it turns out, it is possible to summarize the firm's investment strategy by an indicator known as the expected cost to completion, K. At each stage of the investment, the firm completes part of the R&D, observes any new information pertaining to the sources of uncertainty, and then reevaluates its expectation of how much it will cost to complete the project from that time forward. It can be shown that, a critical level of cost to completion, K^*, exists, such that, if the expected cost to completion exceeds this level, it is not optimal for the firm to exercise its option to invest, or to continue the R&D if it has already been initiated. Conversely, if expected cost to completion is below the critical level, the firm should go ahead and initiate investment if it has not done so already, or carry on with the next stage of the investment.

Pindyck has developed a real options investment model whose features closely parallel the stylized facts of biotechnology R&D discussed above. A simple extension to the model to incorporate the possibility of a termination event completes the necessary structure. At this point, the model's salient features, and its relationship to the sources of heterogeneity specified earlier, are briefly discussed. The model is developed formally in Appendix A.

In the extended Pindyck model, the firm acquires an option to invest in an R&D project of certain value V. The firm is constrained to invest at some maximum per-period rate I, which implies that investment will proceed over multiple time periods. The evolution of expected cost to completion K is stochastic, due to the presence of the three sources of uncertainty specified in the stylized facts. Technical uncertainty and regulatory uncertainty are represented respectively by the parameters β and γ, which are scalars for uncorrelated standard Wiener processes. The termination event, representing uncertainty in the scientific environment, is represented by a memoryless Poisson process with mean arrival rate λ. Note that the two hypothesized sources of heterogeneity – the per-period rate of investment and the level of regulatory uncertainty – are represented by the parameters I and γ. The risk-free rate of interest is given by the parameter r.

Given values for the parameter vector [V, I, r, λ, β, γ], the model can be solved for the firm's optimal investment strategy, summarized by the critical cost to completion K^*. Recall that K^* is interpreted as the maximum level of cost to completion for which it is economically feasible to either initiate the investment - i.e., exercise the option - or continue an ongoing R&D project. If the initial expected cost to completion K exceeds K^*, the firm will not undertake the investment. If the investment is already underway when the evolution of K crosses the K^* threshold, the firm will abandon the project midstream. The level that K^* takes will depend on the exogenous parameters in the model: V, I, r, λ, β, and γ, where I and γ represent the sources of heterogeneity in the biotechnology industry. As the next section illustrates, cross-country differences in these parameters will result in asymmetric decision rules for R&D investment, which in turn generate the international differences in investment behavior which may explain the US comparative advantage in biotechnology.

Comparative Statics

To illustrate the comparative statics of the investment model described above, a benchmark vector of exogenous parameters, [V, I, r, λ, β, γ], is constructed from 1996 US biotechnology industry data. In 1996, the total market capitalization of 294 publicly traded US biotechnology companies was $77 billion. This yields an average market capitalization of approximately $262 million per firm, which is used as a proxy for the capitalized value of a biotechnology firm's R&D. For simplicity, this value is assumed to be certain and time-invariant. In 1996, the 294 biotechnology firms collectively spent $4.7 billion on R&D - about $16 million per firm. Therefore, the maximum per-period rate of investment, I, is set to $16 million per year. This figure can be interpreted as a supply constraint on the availability of investment capital, dictated by the willingness of the capital market to fund biotechnology R&D. Again, it is assumed that this figure is time-invariant. A value for λ is also needed: it is assumed that the mean arrival rate of an R&D termination event is 0.2 on a yearly basis. To complete the calibration, the risk-free rate of interest r is set equal to the 1996 yearly average for the one-year Treasury index, or 5.5%.

Numerically solving equation (6) in Appendix A over a range of values for β and γ, yields a matrix of values for K^* illustrating the relative effects of technical and regulatory uncertainty on the critical value of cost to completion (Fackler 1996). The results shown in Table 1 confirm the point made earlier that technical uncertainty tends to enhance the incentive to invest, in particular by raising the critical level of cost to completion K^*. Regulatory uncertainty, on the other hand, has the opposite effect. Increases in the level of γ, holding β and all other exogenous parameters constant, yield substantial decreases in the critical level of cost to completion K^*. For example, if β = 0.5, an increase in the level of regulatory uncertainty from 0.1 to 0.2 leads to a corresponding decrease in K^* of almost ten percent – from $111.4 million to $102.0 million.

TABLE 1 Impact of Technical and Regulatory Uncertainty on the Critical Cost to Completion K^*

	$g = 0.0$	$g = 0.1$	$g = 0.2$	$g = 0.3$	$g = 0.4$	$g = 0.5$
$b = 0.0$	102.2	92.2	85.5	80.3	75.6	71.1
$b = 0.1$	103.5	93.0	86.2	80.9	76.2	71.6
$b = 0.2$	106.7	95.4	88.2	82.7	77.7	73.0
$b = 0.3$	111.4	99.3	91.6	85.6	80.3	75.3
$b = 0.4$	117.6	104.7	96.2	89.7	83.9	78.5
$b = 0.5$	125.3	111.4	102.0	94.8	88.5	82.7

In terms of cross-country differences in the maximum per-period rate of investment I, if $b = 0.5$ and $g = 0.1$, the effects on K^* are shown in Table 2. As the maximum rate of investment increases, the critical value K^*, below which a firm will initiate investment or maintain an existing project, also increases. This suggests, *ceteris paribus*, that a firm exhibiting a higher value of I will invest under conditions that a firm with a lower I would find economically infeasible. Similarly, the firm with a higher I will maintain an R&D program under conditions that would cause a firm with a lower I to choose termination.

TABLE 2 Effects of Maximum Per-Period Rate of Investment on the Critical Cost to Completion K^*

I	1.0	8.0	16.0	24.0	32.0
K^*	21.1	78.6	111.4	132.6	148.0

Cross-country differences in the maximum rate of investment or level of domestic regulatory uncertainty result in asymmetric decision rules governing investment. For example, a country whose capital markets are either "tight", or whose investors are averse to high-risk investments such as biotechnology, will tend to allocate capital less generously on a per-period basis to its domestic biotechnology firms. On the other hand, firms with access to more capital will tend to innovate faster, earlier, and exhibit more perseverance in the face of mounting R&D costs than firms less well supplied with capital. Therefore, if US biotechnology firms invest at a greater per-period rate, as empirical evidence suggests they do, they will find a source of comparative advantage in this feature of the structure of biotechnology R&D.

Note that the two candidate sources of heterogeneity both serve to increase the critical cost to completion for US biotechnology firms relative to European firms. In particular, the fact that US firms invest at a faster rate and are subject to a lower level of regulatory uncertainty implies that US firms will, on average, adopt a higher K^* than their European rivals.

Dynamic Stochastic Simulation

Dynamic stochastic simulation can be employed to assess the implications of the investment model discussed above. The investment model suggests how biotechnology firms may generate their investment decision criteria in evaluating R&D opportunities. To extend the analysis, it is useful to apply the results of the investment model to a stochastic investment environment representative of that found in the biotechnology industry. To do this, the stochastic investment environment – i.e., the stochastic evolution of expected cost to completion K - in which biotechnology firms operate can be mimicked using computer simulation, and the investment strategy summarized by the critical cost to completion K^* applied within this environment to generate simulated investment behavior.

The simulation mechanics can be summarized as follows. For each iteration of the simulation, a random draw is made from a specified interval for an initial expected cost to completion K. In addition, another random draw is made from an exponential distribution to obtain the waiting time for the first occurrence of a Poisson termination event. With these values in hand, the investment begins. During the initial period of the investment, the firm checks to see if the initial K exceeds K^*: if so, the firm delays investment and observes the evolution of K, which is then driven entirely by the random component stemming from regulatory uncertainty. Should the current value of K fall below K^* at some future date, the firm initiates the R&D project at that time. Otherwise, the firm continues to observe K until the occurrence of the Poisson termination event, at which point the investment opportunity becomes worthless.

Once the R&D project is initiated, the investment proceeds as follows. For each time period, the expected cost to completion is incremented according to equation (1) shown in the appendix, which includes reducing K by the firm's maximum per-period R&D investment, and adding on the random components brought about by technical and regulatory uncertainty, which can be positive or negative. The firm then compares the current value of K to its critical value K^*; if K exceeds K^*, the project is abandoned midstream. Also, if the current time period coincides with the time period associated with the occurrence of the Poisson termination event, the project is terminated immediately. Otherwise, investment continues until expected cost to completion equals zero, at which point the R&D project has been successfully completed.

The simulation was carried out for representative US and European firms. Algorithms for generating the random sequences driving the stochastic processes in the model are from Press *et al*. (1992). The value of R&D, the risk-free rate of interest, l,

and β were assumed to be the same for both firms, and were parameterized as \$262 million, 0.055, 0.067, and 0.5, respectively. Heterogeneity was introduced by setting the maximum per-period rate of investment, I, to \$16 million per year for the US firm, and \$6 million per year for the European firm. These figures are based on the average R&D expenditure in 1996, for publicly traded biotechnology firms in the US and Europe. Finally, the level of regulatory uncertainty, γ, was set to 0.1 for the US firm, and 0.2 for the European firm, reflecting the observation that European firms are subject to a higher level of uncertainty pertaining to the regulatory regime than their US rivals. These exogenous parameters are sufficient to derive the critical cost to completion K^* for both firms, which was \$143 million for the US firm, and \$87 million for the European firm.

Finally, the range of values from which the initial expected cost to completion is drawn was specified. This was chosen to be an interval with a lower endpoint equal to the value ten percent lower than the K^* for the European firm (\$78 million), and with an upper endpoint equal to the value ten percent higher than the K^* for the US firm (\$157 million). The simulation was iterated one million times each for the US firm and the European firm. The simulation results are summarized in Table 3. These results offer a striking illustration of how heterogeneity in the R&D investment process can result in one country rapidly dominating the industry. Note that the US firm exhibits, on average, a time to build of 74 months for successfully completed projects, half of the European result of 147 months. Clearly, the US firm innovates more rapidly on average than its European counterpart.

TABLE 3 Dynamic Stochastic Simulation Results

	US Firm	European Firm
Mean Time to Build (successful only)	74 months	147 months
Projects Not Started in Initial Period	187,101	887,241
Projects Started After Delay	149,661	541,342
Projects Terminated due to Poisson Event	287,201	439,255
Projects Abandoned Midstream	261,408	468,325
Projects Successfully Completed	451,391	92,420

Other simulation results offer more insight into the relative performance of the US and European firms. One reason for the US firm's faster rate of innovation is the fact that, in almost 90 percent of the iterations, the European firm does not initiate investment right away, but instead, delays investment until the current value of K drops below the critical value of cost to completion K^*. In contrast, the US firm is forced to delay

investment in only about 20 percent of the iterations. The necessity of delaying investment has profound implications for time to build, as evidenced by the disparity between the US and European firms in this regard. European firms tend to hold their option to invest in biotechnology R&D, waiting to exercise it at a future date, while US firms are more likely to exercise their investment option immediately. Clearly, this behavior would increase the likelihood of an earlier US dominance in the industry.

Another important factor contributing to the faster US innovation rate is that nearly half of the European iterations end in the project being abandoned midstream, as a result of expected cost to completion accumulating to the point that it exceeds the critical level K^*. This is a consequence of the much lower critical cost to completion employed by the European firm as its decision criterion for abandoning or continuing investment. This disparity has significant implications for the total number of R&D projects successfully completed by each type of firm: the US firm completes the project successfully in almost half of the iterations, compared to less than ten percent of the iterations for the European firm. European firms apply a much more rigorous decision criterion (in the form of a lower K^*) to their ongoing R&D projects than US firms, and as such, tend to abandon projects more readily than US firms as expected completion costs increase.

In summary, the simulation results indicate that, compared to its European rival, a representative US firm initiates more R&D projects, commences investment sooner, innovates more rapidly, perseveres longer in the face of mounting R&D costs, and ultimately, successfully completes more projects. This is a result of the heterogeneity present in the R&D process. Clearly, extension of these results to an industry-level setting suggests that US firms would rapidly dominate the industry, as in fact empirical evidence suggests has been the case in biotechnology. This in turn implies that the sources of heterogeneity present in the R&D process – in particular, international differences in the maximum per-period rate of investment and the level of uncertainty surrounding the regulatory regime – offer a plausible explanation for the US comparative advantage in biotechnology.

Summary and Conclusions

In this chapter it has been shown that a real options approach to investment provides a useful analytical framework for examining the hypothesis that sources of heterogeneity within the biotechnology R&D process offer a plausible explanation for US comparative advantage in the biotechnology industry. Contrary to other research on trade in high technology sectors, it was assumed in this chapter that country's resource endowments are identical, and, that the source of comparative advantage lies within the R&D investment process. In a simulation analysis, it was shown that international differences in the maximum per-period rate of investment and the level of regulatory uncertainty are sufficient to generate asymmetric investment behavior, and therefore identify the world leader in biotechnology.

Given these results, it is logical to ask if policy prescriptions, such as R&D subsidies, can "create" comparative advantage in science-based, high technology industries such as biotechnology. The answer is a qualified "yes": while government authorities can affect the rate of innovation, policy intervention cannot, however, alter the probability distribution of success or failure. Rather, it can only move firms more rapidly toward the realization of the outcome of their R&D initiatives, and encourage a less rigorous decision criterion (K^*) used to evaluate potential and ongoing R&D projects.

This qualification leads to a number of welfare-related issues surrounding the use of policies designed to modify directly the incentives to invest in high technology industries. In particular, if government authorities apply the policy in a blanket form to all high technology industries, one result could be the inefficient subsidization of economically undeserving industries. Industries are not worthy of favorable policy intervention strictly by virtue of their status as high technology enterprise. History has shown that some high technology industries have been successes, such as the computer and microprocessor industries; some are still of undetermined status, such as biotechnology and the Internet; and some may be indisputable failures.

An alternative approach would be to selectively target high technology industries for policy intervention, but this creates problems of another sort: specifically, government agencies would be forced to identify particular high technology industries deserving of policy promotion. Clearly, this would be a process prone to influence from non-economic sources, and of course, outright error. In particular, the uncertainty rampant within high technology industries would make "picking a winner" a challenging proposition. The problem of targeting industries for selective policy support is a prominent criticism of the recent interest in strategic trade policy initiatives (see Krugman 1987).

Given these considerations, a better approach to creating comparative advantage in high technology industries like biotechnology may be to institute macroeconomic policies which liberalize capital markets, encourage productive investment, and facilitate the flow of privately supplied capital. In addition, the level of regulatory uncertainty and capriciousness surrounding the commercialization of new technologies could be reduced. In so doing, the flow of capital to high technology industries would be facilitated and encouraged, yet still administered by private economic decision-makers, who, while not infallible, are likely better placed than government policymakers to assess the relative merits of high technology investment opportunities.

Appendix A

The model presented here is Pindyck's real options model of investment with uncertain cost, extended to include the possibility of a termination event. Consider a biotechnology firm faced with the opportunity to invest in a new R&D project. When completed, the project will yield an asset, i.e., a product or process innovation, worth V with certainty. However, the cost to complete the project is uncertain. The firm holds an

option to invest in this project which it has the right, but not the obligation, to exercise. The expected cost to completion, K, evolves according to:

(1) $$dK = -Idt + \beta(IK)^{1/2}dW + \gamma K dZ.$$

I is the per-period rate of investment, β and γ are scalars representing the level of technical uncertainty and regulatory uncertainty, respectively, and dW and dZ are increments of standard Wiener processes, with mean zero and variance dt.

The value of the investment opportunity, $F(K,q)$, is subject to the possibility of a random Poisson termination event, q, which takes the form:

(2) $$\chi dq,$$

where, $\chi = -F$, and $dq = 1$ with probability λdt, and 0 with probability $(1 - \lambda dt)$. λ is the constant mean arrival rate of a termination event. Occurrence of the event implies that the value of the project instantaneously falls to zero, and the project is therefore immediately abandoned.

In order to determine its optimal investment strategy, the firm solves the following infinite horizon optimal stopping problem using dynamic programming:

(3) $$F(K,q) = \max E_0[Ve^{-\mu T} - \int_0^T I(t)e^{-\mu t}dt].$$

where time to build, T, is stochastic. Asset valuation in a risk-neutral economy is subject to the following relation:

(4) $$rF = -I + E[dF/dt].$$

In other words, the risk-free return from holding the asset must equal the expected net cash flow plus the expected capital gain. Applying Ito's Lemma yields:

(5) $$E[dF/dt] = -IF_K + 1/2\beta^2 IKF_{KK} + 1/2\gamma^2 K^2 F_{KK} - \lambda F.$$

Therefore:

(6) $$(r+\lambda)F = -I - IF_K + 1/2\gamma^2 K^2 F_{KK} + 1/2\beta^2 IKF_{KK},$$

which is subject to the boundary conditions:

$F(0) = V$
$\lim (K \to \infty) F(K) = 0$
$1/2\beta^2 K^* F_{KK}(K^*) - F_K(K^*) - 1 = 0$
Value matching condition: $F(K)$ continuous at K^*.

(6) is then solved numerically for K^*, which is the critical cost to completion.

Endnote

[1]Brian Lavoie and Ian Sheldon are Ph.D. candidate and Professor respectively in the Department of Agricultural, Environmental, and Development Economics, The Ohio State University.

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