The economic theory of contractual R&D: With an application to the biotechnology industry.

by

Yuki Iidaka

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Abstract

Since the late 70s, there has been the expansion in the biotechnology industry of contractual R&D whereby a large established firm contracts out some research projects to a small research-intensive firm. There have been some arguments as to the causes of the expansion. However, there have so far been no discussions on the consequences of the expansion on market outcomes.

This thesis examines how this expansion will affect profitability, social welfare and, possibly, industry structure in the biotechnology industry. In order for that, I set up a model for contractual R&D and in-house R&D, which is the conventional arrangement whereby firms carry out all R&D internally, and examine market outcomes under these organizations. Then using the results and the facts on industrial biotechnology, I will advance a conjecture on the impact of the expansion on market outcomes.

This thesis starts to overview the biotechnology industry and the literature on research joint ventures with spillovers, from which my main model is derived. The next two chapters analyze profitability and social welfare under in-house R&D and contractual R&D. The last chapter analyzes under which R&D organization industry concentration at the R&D stage will be reduced more. It also analyzes the resultant social welfare.

My conjectures on the impact of the expansion are as follows. Whether the expansion will lead to the higher profitability depends on the degree of competition in a final good market and the nature of R&D. On the other hand, the expansion will result in the larger social welfare regardless of these factors. The impact of the expansion on industry structure rests on the nature of R&D, and, once the impact of industry structure is taken into account, the expansion has ambiguous effects on social welfare.

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Contents

Chapter 1. Introduction

Contractual R&D is the R&D arrangement whereby a large established firm contracts out some research projects to a small research lab and funds its research. In return, the lab transfers a research output to its partner firm if it succeeds in R&D. Contractual R&D is quite often regarded as an alternative to the conventional in-house R&D where firms carry out all R&D internally.

Contractual R&D started more or less as a marriage of convenience. In the 70s few large firms possessed in-house technical expertise of the then latest biotechnology. Thus, large firms had to turn to small labs which were usually equipped with the advance techniques of biotechnology. In the meantime, labs too had to rely on large firms as they lacked assets to commercialize their research output such as the familiarity in the complex regulatory procedures, large scale manufacturing facilities, and worldwide marketing network, all of which large firms had.

Since then, contractual R&D has been expanding in the biotechnology industry. As reported in Lerner and Merges (1998), in the US biotechnology industry in 1981 the number of filed cases of alliances was just 30, while in 1997 it went up to 171. Bio/Technology (1994) expected alliances between European biotechnology firms, pharmaceutical firms, Japanese firms, US agricultural firms to increase substantially. According to The Economist (1998), the proportion of outsourcing in the R&D budget of pharmaceutical firms was about 9 % in 1990 but shot up to about 17% in 1996. Moreover, this trend is likely to continue.

Some reasons for this expansion have been advanced in the management literature. For instance, as biotechnology R&D has become more and more inter-

disciplinary, it has become increasingly difficult for large firms to carry out internally all the various activities necessary for innovations. Or, sometimes, the expansion is attributed to some alleged advantages of contractual R&D over in-house R&D. It is said that a firm can mitigate capacity problem or reduce risks in R&D by using contractual R&D.

Whatever the causes, to our best knowledge, so far there has been no discussion about *the consequences of the expansion of contractual R&D.* It is hardly clear whether or not the expansion will lead to higher profitability and whether it will result in a socially more efficient market outcome.

The main aim of this thesis is to examine how this expansion may affect profitability and social welfare in the biotechnology industry. To this end, I will set up a theoretical model for contractual R&D and in-house R&D, and derive results on profits and social welfare under these organizations. Then using the results and some reported facts of the biotechnology industry, I will advance a conjecture on the impact of the expansion on profitability and social welfare.

The organization of the thesis is as follows.

Chapter 2 presents a brief outline of the biotechnology industry. It starts with the origin of biotechnology and moves on to its industrial applications. Differences between biotechnology and conventional technologies that were (and, sometimes, still are) used in biotechnology-related industries will be mentioned. Then I show how large firms at first reacted to the emergence of biotechnology. My account is mainly concerned with the build-up of in-house expertise in biotechnology, use of contractual R&D, and equity investment in labs by large firms. Then I present a detailed account of contractual R&D and its alleged potential advantages and disadvantages over in-house R&D. Finally, I will explain how my main model is set

up so as to capture some key aspects of the biotechnology industry.

Chapter 3 surveys the literature on research joint venture with spillovers, from which my main model is derived. First, I overview some key papers and show how their results are determined by the rate of spillover. Then I will briefly examine papers that criticize some of the underlying assumptions and show how the amended models incorporating the criticisms can alter some well-established results. Finally, I will explain how my main model differs from the ones in the literature.

Chapter 4 examines profitability and social welfare under in-house R&D and contractual R&D by setting up the following model. Two multiproduct firms plan to conduct R&D aimed at two *independent* markets. If a firm uses in-house R&D, it runs two projects in parallel. If it resorts to contractual R&D, it delegates one project to an independent profit maximizing lab while carrying out the other project on its own. If a project is successful, a firm gets the research output transferred internally or from its partner lab and reaps the payoff in a market.

When a firm uses in-house R&D, the probability that its R&D unit succeeds in a project depends on the following four components; (1) the amount of the information generated from the investment made in the particular project; (2) the amount of the information *internally* passed by researchers of the other project to those of the particular project; (3) the information which leaks out of the *other* units; (4) the size effect which would lower productivity of a firm due to the split of its R&D personnel to two project teams. If contractual R&D is used, the probability depends only on the first and the third components.

Each R&D unit sets the level of the investment on a project non-cooperatively and simultaneously to maximize its expected profits. When a firm uses in-house

R&D, it chooses the level of *both* projects. Under contractual R&D, it does so *only* on one project and its partner lab on the other project.

In this chapter, I confine ourselves to two cases: one where both firms use in-house R&D, which I call the Integrated (*I*) regime, and the other where both use contractual R&D, which I call the Separated (*S*) regime. I then compare profitability and social welfare under these two regimes.

On the basis of the main results in the model, I advance a conjecture on the impact on market outcomes of the expansion of contractual R&D in the biotechnology industry. Notice that the *I* regime can be viewed as the case where there is no expansion of contractual R&D while the *S* regime as the one where there is (so that firms use contractual R&D). Thus, in order to derive the conjecture, I will use facts about the biotechnology industry to identify the likely situation there. (This includes inference of the relevant parameters obtained from empirical literature). Then, I will compare the outcome of both regimes in the situation. If profitability and social welfare are larger in the *S* (*I*) regime, then I conclude that the expansion in contractual R&D will result in the larger (smaller) profits and social welfare.

Chapter 5 extends the previous analysis by examining , in addition to the *I* and the *S* regimes, the Hybrid (*H*) regime where one firm uses in-house R&D but the other contractual R&D. Here, the model assumes information leakage across R&D units *only after R&D* and *only across units involved in the same projects*. Comparing the *I* regime with the *H* (*S*) regime, I will advance a conjecture about the impact of *partial* (*total*) expansion of contractual R&D on market outcomes.

Chapter 6 analyses the impact of the expansion of contractual R&D on the industry structure of the biotechnology industry.

A very noticeable change which biotechnology brought to the biotechnology industry in the 80s was a reduction in industry concentration *at the R&D stage*. In Chapter 2 I show that large multiproduct firms, which were equipped with biotechnology, diversified their in-house R&D into new fields removed from their traditional expertise. The most notable example was substantial entry into the pharmaceutical industry by non-pharmaceutical firms.

However, the recent expansion of contractual R&D means that nowadays these multiproduct firms are often involved in R&D in several industries via contractual R&D. For instance, a chemical firm runs a project for chemical development on its own but delegates a project for drug development to an independent lab in the pharmaceutical industry.

I will examine whether such use of contractual R&D could facilitate further a reduction in concentration. To this end, I will consider two cases: the Integrated (I) regime where there is no contractual R&D so that all N^I firms rely on their in-house R&D and the Separated (S) regime where there is *total* expansion of contractual R&D so that all N^S firms use contractual R&D. Then I will investigate whether N^I is greater than N^S in free entry equilibrium. After examining how industry structure is affected by the choice of R&D organization, I will also analyze the effects on social welfare.

On the basis of the results, I will also advance a conjecture on the impact of the expansion of contractual R&D on the industry structure in the biotechnology industry and its welfare implications.

Chapter 6 extends the analysis of Chapter 4 to the more general N-firm oligopoly case and, for simplicity, assumes no information leakage across units and Bertrand

competition in the final-good market.

In addition to the I and the S regimes, I will briefly analyze the case where only *some* firms use contractual R&D, which I call the *H* regime. By comparing the *I* regime with the *H* regime, I will assess the impact of *partial* expansion of contractual R&D on industry structure and welfare.

Chapter 7 summarizes the main results. The result on profitability shows that given the success probability in the *I* regime, whether a firm can earn larger profits under in-house R&D or contractual R&D depends on two organizational factors, the size effect and the cross fertilization rate. However, which organization is socially preferable depends just on the above two organizational factors. Chapter 6 shows that how the organizational choice of firms will affect industry structure at the R&D stage is determined by the relationship between the two organizational factors and the success probability in the *I* regime. Moreover, if the impact of industry structure is taken into account, the welfare comparisons under two R&D organizations too will vary depending on the probabilities of success.

Using these results, I advance a conjecture on the impact of the expansion of contractual R&D in the biotechnology industry on market outcomes. Whether this expansion will lead to the higher profitability depends on the degree of competition in the final good market and on the nature of R&D. On the other hand, the expansion will result in larger welfare regardless of these factors. Whether the expansion will result in more concentration at the R&D stage depends on the nature of R&D, and, once the impact of industry structure is taken into account, the expansion has ambiguous effects on social welfare.

Chapter 2. Overview of the biotechnology industry

1. Introduction

This chapter presents a brief outline of the biotechnology industry. Section 2 will explain biotechnology itself, and section 3 will outline its industrial applications. Section 4 will show the response of large established firms in the industry to the emergence of biotechnology. Section 5 will be concerned with contractual R&D especially as compared with in-house R&D.

2. Biotechnology

Biotechnology, which is a general term encompassing a range of new techniques, stemmed from two main developments. [1] The first one was biology. Since the 50s, there were a series of discoveries about genetic materials such as the structure of DNA and its role in the building of proteins. In 1953, James Watson and Francis Crick discovered that DNA was a double helix, two intertwined strands each composed of chains of four different chemical bases, called A, C, G, and T. Within a strand the bases could be arranged in any order. However links between strands could be made only between two specific pairs (A to T, C to G). Later in the 60s, Crick and his colleagues postulated that DNA bases were so organized as to represent a code to specify the assembly of amino acids into proteins. It turned out that the codes for all 20 of the amino acids used to make proteins were found to be

[1] The Economist (1988) provides an excellent account about this.

different groups of three of DNA bases in sequences. These trinities are called codons. A stretch of codons together formed the instructions for the building of a protein. Each stretch was in effect a gene. The second development was genetic engineering, which was founded on the understanding of DNA. The first successful gene transfer (from one organism into bacteria) occurred in the early 70s. With few exceptions, the same 20 amino acids and the same four genetic letters are used throughout nature. The universal molecular language of nature is what enables scientists to snip a gene out of one of species and splices it into another so that the host species recognizes the foreign gene spliced into it, obeys its instructions and makes a foreign protein. The basis of genetic engineering, recombinant DNA, was developed in 1973 by two Californian scientists, Herb Boyer and Stanley Cohen.

These developments led researchers to become aware of the practical applications of biotechnology: the mass production of rare but desirable proteins, usually drugs, by transferring genetic instructions on the production of the protein, which is encoded in DNA, into rapidly multiplying living cells and using them as a living factory; and the improvements of the organisms themselves, usually by the addition to their DNA of a new gene which confers a desirable quality to the best organism (pest resistance to crops, for instance).

3. Industrial applications of biotechnology.

In the pharmaceutical industry biotechnology enabled researchers to develop new drugs by using natural proteins that control many chemical process in the body. [2]

[2] See The Economist (1987).

Prior to the emergence of biotechnology, the discovery of new drugs was based on the systematic examination of synthetic chemicals for their physical effect. Researchers used to examine chemicals, find new ways to attach hydrogen and oxygen atoms to a ring of carbon atoms, and create new compounds. Biotechnology led researchers to attempt to turn proteins into useful new drugs, which were known to have specific beneficial effects. Biotechnology made such an attempt possible in two ways. First, it enabled researchers to produce proteins which were too complex to be synthesized in the lab. Second, such proteins were present in such small quantities to make them difficult even to analyze but some new techniques could solve this supply problem. Moreover, availability of such previously rare proteins enabled researchers to figure out the structure, i.e. a three dimensional view, of proteins by using computers. They could gather much useful information of proteins and, then, *design* a protein for a new drug by using such information. That was not the case when researchers used to synthesize drugs chemically. For there was often no way of knowing how a new drug would behave once it was synthesized.

In the chemical industry, biotechnology has been used largely to develop new processes that produce existing chemicals more cheaply. [3] Production of chemicals involves catalysts to speed up reactions. The conventional method employed heat as the catalyst, sometimes combined with metallic or other catalytic substances. These processes required very high temperatures and pressures. On the contrary, biological synthesis of chemicals uses natural enzymes as catalysts and operates at low temperatures and pressures. According to Smith (1996), the advantage of the

[3] See The Economist (1981).

latter is that enzymes in a bio-process can catalyze reactions in near natural pH and function only on certain types of compounds. These can result in high-quality products, fewer by-products and simpler purification. [4] Here, genetic engineering can be used to enhance the activity of enzymes, to permit them to function in a changed environment and so on. [5] Also, the bio-process improved by genetic engineering can produce some chemical products such as ethanol, glycol, ethylene, oxide, lubricants, propylene glycol, pure crystalline fructose, ultra-pure chemicals, olefins and paraffin. [6]

Daly (1985) briefly summarizes the role of biotechnology in other industries.

The food industry has been largely concerned with process innovations such as modification of the microbial processes used in cheese making, brewing, baking etc. or use of new specialty chemicals such as enzymes.

The agribusiness industry, especially as animal drugs and growth promoters, is similar to the pharmaceutical industry. Thus the main contribution of biotechnology is development of new products as in the pharmaceutical industry.

The potential application of biotechnology in commodity chemicals has been to achieve cost reduction either by use of biological feedback (biomass) and/or

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[4] Smith (1996) mentions some disadvantages of this bio-process; (1) it can be easily contaminated with foreign unwanted micro-organisms, (2) it is extremely slow relative to conventional chemical process, (3) the desired produce is usually present in a complex product mixture requiring separation, (4) it needs to be given, handled with, and disposed with large volume of water.

[5] Contrary to the initial expectation, these bio-processes have not been used as substitute of existing processes. Rather they are used when no alternative process was available.

[6] See The Economist (1981).

through replacement of chemical technology by microbial or enzymatic processes.[7]

Liquid and solid wastes are broken down in waste treatment plants largely through the action of microbes. Biotechnology can produce enzymes or other substances that hasten or further this process. For example, biologically derived flocculants, would be very useful for separating and thickening solids during treatment.

These inter-industry implications of biotechnology are due to the nature of some technologies. Above all, the one called recombinant DNA has a wide range of industrial applications. The main objective of this powerful technique is to transfer genes from other organisms into some bacteria, which are single-celled, reproduce quickly and carry plasmids, small loops of self replicating DNA. [8] Its industrial applications are indicated in Table 1. In addition to this technique, those dealing with genes of microbes too can affect various industries using fermentation processes. Fermentation technology or so-called bioprocess technology is derived from the use of micro organisms for the production. Biotechnology can raise their productivity and widen the range of products. Smith (1996) shows that new fermentation products from improved microbial process would be

- bulk of essential primary metabolites such as acetic and lactic acids, glycerol, acetone, butyl alcohol, organic acids, amino acids, vitamins, and polysaccharides;

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[7] Here, biotechnology was not expected to have a significant impact until 2000 or after that. For it was still more economical to use petroleum feedstock and the rate of substitution of biological for chemical process would depend on petroleum feedstock availability and price.

- secondary metabolites (metabolites that do not appear to have an obvious role in the metabolism of the producer organism) such as penicillin, streptomycin, cephalosporin, giberellins, etc.;
- many forms of industrially useful enzymes, e.g. exocellular enzymes such as amylases, pectinases and proteases, and intracellular enzymes such as invertase, asparaginase, restriction endonucleases, etc.

Table 2 summarizes such new products in each industry.

4. Build-up of in-house expertise in biotechnology by large firms.

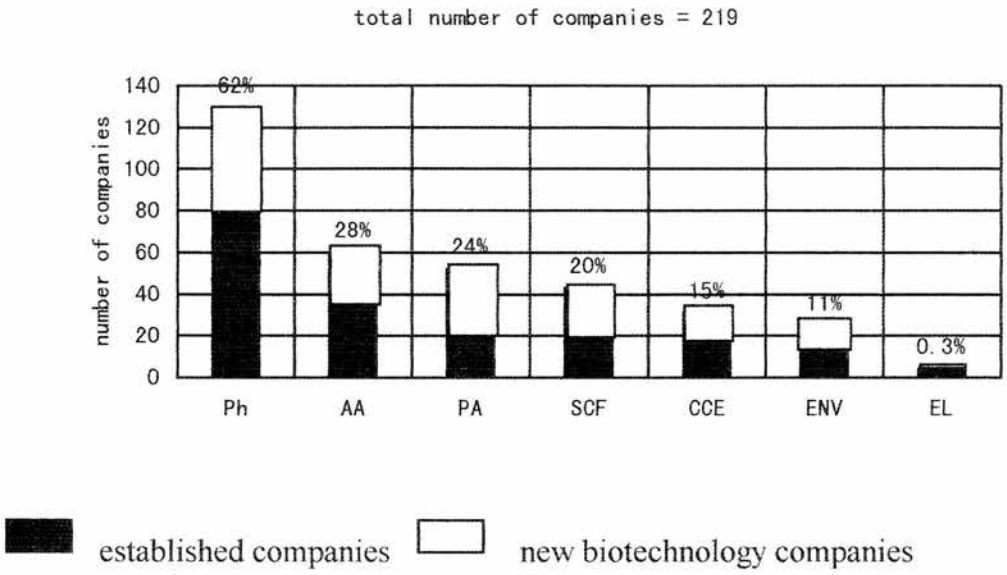
Industrial applications of biotechnology began in small research intensive firms, which were established by academics-turned-entrepreneurs.[9] For, most of new techniques of biotechnology originated from universities, and researchers in such firms had close contacts with them.

Unlike these small firms, large established companies did not have their own in-house expertise in biotechnology. Yoxen (1983) says that, except for a few, such as ICI and Schering, most of them were rather skeptical about biotechnology at first. In 1977, Genentech, one of the successful small research firms, succeeded in developing human insulin with recombinant DNA. That made all the more obvious to many large firms the commercial potential of biotechnology and persuaded them

[8] The Economist (1988) shows how human insulin can be produced with this technique.

[9] See The Economist (1988).

Figure 1. Percentage of firms in the US pursuing applications of biotechnology in specific sector.[10]



Source: Office of Technology Assessment (1984).

into getting involved in it. [11] Table 3 provides a list of small research firms and large established firms applying biotechnology in the US and the targeted commercial areas of their research. Figure 1 illustrates the percentage of US firms

[10] Ph: Pharmaceutical , AA: Animal agriculture, PA: Plant Agriculture, SCF, Speciality Chemical and Food, CCE: Commodity Chemical and Energy, Env: Environment, El: Electronics.

[11] Sometimes, large firms sought licensing of products already developed by small firms, research joint venture with them, acquiring them or R&D limited partnership with them. The partnership was usually used to fund clinical trials or production scale up, not R&D. The investors (large firms) invested their money not in the company but in some particular projects. The small research firms were contracted by partners to perform the tasks needed to bring the product. This financial arrangement is an important method of securing funding and shifting the risks of launching a new product to the limited partner. Below we will show the cases other than these: build-up of in-house expertise in biotechnology by large firms, use of contractual R&D by large firms, and equity investment in labs by them.

pursuing biotechnology R&D in specific applications areas.

According to the Office of Technology Assessment (1984) (OTA hereafter), the most obvious course of action of large firms was to build up their in-house expertise in biotechnology in recombinant DNA, immunology, and other new techniques. This was sometimes autarchic. Several large US pharmaceutical companies spent large amounts to build new facilities,[12] e.g.

- G.D. Searle - a $ 15 million pilot plant to make proteins from rDNA organisms;
- DuPont - a $ 85 million life science complex;
- Eli Lilly - a $ 50 million Biochemical research center with emphasis on rDNA technology and immunology, and a $ 9 million pilot plant and lab for rDNA products;
- Bristol Myers spent $ 10 million in an alpha interferon production plant in Ireland.

Companies from other sectors too made substantial investments in biotechnology.

In Europe, large firms were not so actively involved in biotechnology as their US counterparts. However, some of large pharmaceutical companies invested heavily in biotechnology in the early 80s,[13] e.g.

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[12] Though OTA (1984) does not indicate exactly when the investment below took place, it is quite likely to be sometime between the late 70s and the early 80s.

[13] According to OTA (1984), in the second, the third, and the fourth cases, the investment took place sometime between the late 70s and the early 80s.

- Hoffman-La-Roche - $ 59 millions on biotechnology R&D in 1981;
- Ciba-Geigy - $ 19.5 million biotechnology center in Switzerland and $ 7 million agricultural biotechnology laboratory in north Carolina.
- ICI - the world's largest continuous bioprocessing plant;
- Elf Aquitaine - (1) owning Sanofi, a pharmaceutical company that was applying biotechnology to human and animal health in areas including diagnostics, neuropeptides, serums, vaccines, and antibiotics, (2) establishing Elf-Bioindustries and Elf-Bioresearch to develop biotechnology in the foodstuffs and agricultural sectors, and (3) building a $ 10 million genetic engineering plant to support some of its new biotechnology R&D;
- Rhone Poulenc - establishing a small specialty biotechnology subsidiary in 1980.

Sometimes, large firms relied on contracts with universities, small firms, or equity investment in small firms to gain in-house expertise.

As mentioned earlier, the original source of new technology was academic laboratories. Kenny (1986) shows that established firms had paid particular attention to funding academic research and to linking their own research programs with universities in the early days. The main aim was to promote technology transfer from the universities to the firms and also to have a window on new basic science which would be useful for them in the future. In many contracts, large firms even invested money merely to discover the potential of biotechnology.

Conversely, because of their technological expertise and early role as contract research companies, small research firms played a similar role to large firms. According to OTA (1984), they helped large companies evaluate the feasibility

and suitability of using the new technologies in their existing lines of business or new avenues for diversification. Frequently, large firms maintained multiple research contracts with small firms to evaluate several applications simultaneously or to evaluate the same application from different perspectives.

OTA (1984) says that the expansion of in-house R&D expertise of large firms went on in parallel with their active equity investment in small firms. Since 1978, such equity investments, often accompanied by research contracts, have been a popular way for large firms to gain expertise in biotechnology. Between 1978 and 1980, there was a drastic increase in investment. The investment was made notably by US companies from a variety of industries, [14]e.g.

- Monsanto (chemicals) - $ 20 millions in Biogen and $ 5.5 million in Collagen.
- Lubrizol (chemicals) - a second equity investment in Genentech totaling $ 15 million.
- Fluor (engineering) - $ 9 million in an unspecified small company.
- Koppers (mining) - expanding its equity position in Genex by investing $ 12 million. [15]

For large firms, simply paying contract fees to the startup provided little insight into novel biological R&D processes which small firms were involved in. In many cases, large firms purchased enough equity to be awarded a seat on the startup's

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[14] According to OTA (1984), in the cases below the investment took place sometime between the late 70s and the early 80s.

[15] These investments peaked in 1982. A growing commitment among large firms to in-house programs in conjunction with investments already made may have contributed to the sharp drop.

board of directors. The seat allowed large firms not only to insure their investment but also to discover what opportunities they felt were worth pursuing. Such knowledge was important for them during the stage where they were still groping for commercial targets. Even after large firms acquired in-house research facility, the informational nexus of biotechnology startups, with their scientific advisors (full time university faculty members) and research scientists offered them ready access to information about the latest research breakthroughs.

These investments gradually paid off, and large firms came to acquire some novel biotechnology to carry out R&D, according to Whittaker and Bower (1994). Moreover, during the transition period, many large firms diversified their R&D into the areas removed away from their traditional expertise. As OTA (1984) says, the most noticeable was entry into pharmaceutical industry by non-pharmaceutical firms via R&D diversification. This was because the industry was deemed to be most profitable among all biotechnology related industries. Table 4 shows a list of non-pharmaceutical Japanese firms which diversified their in-house R&D into pharmaceutical industry. Besides, Goto (1994) shows that some non-pharmaceutical Japanese firms entered other biotechnology related non-pharmaceutical industries as well.

5. Advantages/disadvantages of contractual R&D over in-house R&D

Contractual R&D is an R&D arrangement whereby a large firm delegates a R&D project to a small research firm and funds the research. In return, the latter, if it succeeds in R&D, transfers the research output to the former. In the management literature, this arrangement is regarded as an alternative to the conventional *in-*

house R&D whereby a firm carries out all R&D on its own. I mentioned earlier that large firms used contractual R&D for technological transfer. However, in many cases of contractual R&D, a small firm ran a R&D project to develop some specific product or conducted toxicology or clinical research *on behalf of* large firms.[16] Table 5 shows a list of cases of contractual R&D. [17]

Contractual R&D in the biotechnology industry started as a marriage of convenience. As mentioned earlier, the lack of in-house expertise in the early days forced large firms to turn to small research firms. However, according to OTA (1984) and Freeman and Barley (1990), small firms too had to rely on large ones. For the latter were familiar with the complex regulatory procedures and had large scale manufacturing facilities and worldwide marketing networks. These were what small firms lacked to commercialize their research outputs. In this sense, the relationship between large firms and small ones was complementary.

The development of contractual R&D went on in parallel to changes in the nature of R&D, particularly in drug developments. Della Valle and Gambardella (1993) say that when drug discovery depended on random screening of many molecules, the key assets for innovation was economies of scale. The higher the scale of experimentation or the more experiments over time, the higher the chances of drug discovery. Scale and learning could not be bought and sold, and were resources that had to be created and utilized by the same firm. The increasing scientification of drug development research mentioned earlier made it possible for useful

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[16] Nowadays, contractual R&D refers to this sort of arrangement rather than technological transfer.

[17] Contractual R&D took place most actively in pharmaceutical industry. It was because biotechnology was utilised there most. Also, large firms wanted to be involved in R&D for profitable drugs with the help of research expertise provided by the small firms.

information for innovation to be divided into pieces; information about the structure of receptor A, the biological action of drug X, etc. Then the pieces could be exchanged amongst specialized parties provided that intellectual property rights adapted. That is, small firms could invest in R&D and sell their research outputs to larger firms with downstream capabilities. Or large firms could assemble the necessary pieces of information for their R&D. This favors specialization and division of labor. In fact, this is said to be one of the reasons about why innovation and marketing of new drugs increasingly result from a network of different agents.

Small firms, with their flexible and informal organization, were (and still are) considered to be more efficient in the production of ideas or R&D than large ones. According to Daly (1985), particularly, Genentech, Genex, Cetus, Centocor, and Celltech attracted much attention from large firms for their research excellence.

Genentech was involved in health care application in biotechnology. Their first contract was to provide genetically-engineered insulin producing bacteria to Eli Lilly in 1978. Genentech received a payment for its research and an unspecified royalty on all of Lilly's bacterially produced insulin sales. Eli Lilly obtained exclusive worldwide rights for manufacturing (which Genentech gave up) and marketing. The next contract was to produce human growth hormone bacterially with AB Kabi, a Swedish company which is the largest supplier in that product. Kabi received a worldwide exclusive manufacturing and marketing rights. In return, Kabi funded the research. (Genentech secured the manufacturing right for the product). In 1980, Genentech and Hoffmann-La Roche reached an agreement to develop jointly alpha and beta interferons. Genentech developed the bacteria and supplied a portion of the interferon needed for clinical trials. In return, Roche funded Genentech's research and, also, sponsored clinical trials. The contract

secured worldwide exclusive marketing rights in return to royalty payment. In the case of tissue type plasminogen activator, Mitsubishi Chemical and Kyowa Hakko were given marketing rights in Japan in return for research funding.

Genex conducted R&D mainly in fine chemical. It completed contracts with

- Green Cross & KabiVitrum in 1983 for the development of a microorganism that produces human serum albumin;
- Schering for an amino acid-producing organism.

Genex was also involved in a contract with Yoshitomi Pharmaceutical Industries of Japan to produce inteleukin-2 through genetic engineering techniques. They also entered a five-year contract with Bendix to develop protein engineering technology necessary for constructing novel proteins with desirable characteristics.

Unlike Genentech or Genex, Cetus initially developed a wide range of interests in diverse industries including energy and biomass, sweeteners, fine chemicals, bulk chemicals, agriculture and pharmaceuticals. However, after Standard Oil of California (Socal) decided to pull out of collaboration with them, the company concentrated on three main areas, health care, (especially cancer therapeutics and diagnostics), agriculture products, and industrial processes and products. They carried out a range of contract R&D and developed a number of products in association with other companies. They developed

- improved strains of bacteria for making the antibiotics Sisomycin and Netromycin which were marketed by Schering- Plough;

- a monoclonal antibody for use in low back pain diagnosis that was marketed by Cappel laboratories;
- a vaccine for the prevention of scours in newborn pigs marketed by Norden Labs.

The company also signed a research agreement with Shell Oil Company to develop microbial methods for interferon.

Centocor concentrated on human health care, in particular cancer diagnostics and therapeutics. Centocor signed an agreement with Abbott for marketing two cancer diagnostic kits. They had various research agreements with leading biotechnology and clinical institutions such as the Wistar Institute, the Dana Farber Cancer institute, Memorial Sloan Kettering Institute, Massachusetts General Hospital. The company used the contract with medical and research centers to conduct research and testing on their behalf and licensed antibodies which could subsequently be developed into assays, propriety to Centocor. They were relying not only on other established companies to market its products, but also on external academic researchers to amplify the R&D resources available to it. The commercialization of research results performed outside the company was unconventional for small firms but speeded up their process of new product introductions.

Celltech concentrated on the application to health care of two new technologies, recombinant DNA and monoclonals. However, the emphasis was placed on the monoclonal antibody area. They possessed facility for bulk production of monoclonal antibodies for other companies, which attracted a wide range of contract. They entered into agreements with

- Serono Labs Inc. for the development of human growth hormone, a drug which has already been developed by Genentech; [18]
- Sankyo Company of Japan for the development of calcitonin and tissue plasminogen activator, and the product was expected to go into clinical trials 1985-86;
- Sankyo for the development of macrophage activating factor and tumor necrosis factor.

As with Centocor, external relationships played an important part for Celltech. It had the first option right on Medical Research Council research results and it had links with academic institutes.

Nowadays, unlike in the days of the above examples, large firms can match small firms in many aspects of biotechnology expertise. Therefore they can conduct more R&D on their own than before. Nevertheless, Bio/technology (1994), Whittaker and Bower (1994), and Lerner and Merges (1998) report that large firms have been engaged in *more* not fewer R&D partnerships. This implies that they are looking for something more than a specific technical expertise.

There are three alleged advantages of contractual R&D over in-house R&D apart from gaining specific expertise from small firms. First, it is argued that contractual R&D allows large firms to change their focus more easily and cut its losses.[19] For instance, in contractual R&D, the large firm can easily choose to terminate the

[18] The Celltech product was to be manufactured using mammalian cells.

[19] See The Economist (1998).

project if its partner small firm does not make satisfactory progress. In in-house R&D, there are political difficulties with terminating projects. Besides, at the very least, the large firm could be left with a team whose skills can no longer be employed within itself once the project of the team is complete.

Secondly, Whittaker and Bower (1994) say that contractual R&D reduces risks and costs in the potentially risky business. Much of the new technology is relatively untried so that there is little guarantee that a new technology will yield a reliable product. If it fails, then the cost of the failure could be substantial. Farming out a research project to a lab makes it possible for a firm to share (and, thus, reduce) the risk with a lab.

The third one is concerned with a capacity problem in R&D. A firm is subject to the R&D budget and the R&D personnel, i.e., the capacity. If it runs all projects internally with the capacity, it has to spread those input to its numerous projects. That reduces the size of each project team, which can have an adverse effect on its productivity. Delegating a project to a lab and, subsequently, reallocating the budget and the personnel to the smaller number of projects can mitigate the adverse effect. Halliday *et al* (1997) showed that many large firms in their survey used contract R&D due to the capacity problem (and, to the lesser extent, specific expertise of small firms). Gittins (1997) argues for contractual R&D from this viewpoint.

However, there are two possible advantages of in-house R&D over contractual R&D. First, a large firm can coordinate its entire R&D activities optimally such as allocation of resources or the activities across various projects when it has the complete control over them. If a project is delegated to a lab, a firm loses the control over the project partially or, possibly, completely. The consequential

difficulty in the coordination can adversely affect profits which would be realized from the project.

The second one is concerned with internal project cross-fertilization. OTA (1984) says that large firms are generally process-oriented multiproduct firms which could and, in fact, did operate in more than one industrial sectors such as pharmaceuticals, energy, chemicals, and food. This means that they have to run several projects in parallel. I mentioned earlier that many techniques of biotechnology had various industrial applications. Thus, if a large firm carries out several projects simultaneously aimed for different innovations, there could take place project cross fertilization within the firm. The more projects they run, the more they are likely to get that from more directions. Due to the nature of biotechnological techniques, such cross fertilization effect is likely to be non-trivial. Large firms which run all projects internally can take full advantage of that, which would enhance innovation and raise the chance of success in their internal projects.[20] Henderson and Cockburn (1996) find that such internal spillovers play a significant role in the pharmaceutical firms in their sample.

6. Relation with the present work.

My models in Chapter 4, 5, and 6 are relevant to the biotechnology industry as far as the following aspects are concerned.

First, I analyze the behavior of *multi*-product firms in the industry, which operate

[20] According to The Economist (1998), Roche and Glaxo reorganised their in-house R&D structure so as to enhance such cross fertilisation.

in a few *independent* industries. OTA (1984) says that large firms in the industry is usually a multi-product firm that seeks improvement in production technology or development of new products. Moreover, the build-up in in-house R&D expertise by them and the inter-industry nature of biotechnology enabled them to enter the industry other than their traditional area, e.g. entry of a food firm into the pharmaceutical industry. I aim to apply our analysis to these firms.

Second, our model features cross fertilization and the (negative) size effect in in-house R&D. [21]

Cross fertilization will be modeled as spillovers between researchers of one project and those of the other(s), i.e., intra-unit externalities. As such spillovers occur within a R&D unit, it is reasonable to think that *all* the information about one project is passed to those involved in the other. Thus, the extent of the externalities depends on how much useful the information is for the latter researchers, which rests on the nature of R&D projects within a unit. As techniques of biotechnology usually have a wide range of industrial applications, such externalities are sure to be present within a multi-product firm, which we will be considering. For instance, those involved in drug development could pass some information to those who are in charge of development of amino acids.

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[21] In my essays, I will focus on the difference in the information assimilation/generation process between In-house R&D and contractual R&D. Thus I will leave out some other alleged organisational (dis)advantages, which are not really related to this. For instance, that contractual R&D enables firms to save costs of hiring staffs whose manpower will not be needed after a particular project terminates is not related to the information generation process. As to risk sharing between a firm and a lab mentioned above, the point of that is whether a firm can supply goods acceptable to consumers. That depends largely on consumer's taste, advertising, or quality improvement by manufacturing division.

On the contrary, the size effect is modeled as something that will adversely affect the productivity of a firm. *Given* the R&D personnel of a firm, the more projects it carries out, the less researchers each project has, and, thus, the smaller the size of each project team is. That will adversely affect its ability to assimilate and generate information to achieve success in R&D. Note that if a firm delegates some project(s) to a lab, it can concentrate on the smaller number of its internal projects. That enlarges the size of its project teams and, thus, weakens the size effect. I call this the specialization effect.

Finally, I assume complete coordination in R&D activities by a firm in In-house R&D and complete delegation of a R&D project to a lab in contractual R&D. This not only highlights the difference between two organizations. Also this formulation means that in In-house R&D a firm internalizes cross fertilization externalities while it externalizes them in contractual R&D. [22]

[22] I mentioned equity investment by large firms on small labs. This could mean that large firms meddle into some R&D activities by their partner labs. In our essays, solely to simplify the analysis and to contrast two R&D organisations, I will rule out any interference by large firms in contractual R&D.

Appendix A.

Table 1. Industrial applications of Recombinant DNA

Pharmaceutical	polypeptide drugs and vaccines, new or cheaper antibiotics, monoclonal antibodies for diagnosis and therapy
Food	modified yeast for alcoholic beverages, elevation of levels of microbial enzymes
Wastes	genetically modified inocula, transfer of degradative enzymes to a single organism
Agriculture	plant and animal breeding, biological pesticides, incorporation of nitrogen fixing ability
Chemicals	new enzyme catalysts and elevated levels of existing ones, ore leaching with genetically modified inocula
Energy	thermophilic organisms for ethanol production, transfer of key genes to faster growing and more easily grown organisms, tailor made organisms for enhanced oil recovery

Source: Dunnill and Rudd (1984).

Table 2. Fermentation products according to industries.

Industry	**Products**
Chemical	Ethanol, [a] acetone, [a] butanol, [a] Organic acids [a](citric, itaconic) Enzymes, [b] Perfumeries, [b] Polymers (mainly polysaccharides), [b] Metal beneficiation, [c] bioaccumulation and leaching [c](CU, U)
Pharmaceutical	antibodies, diagnostic agents (enzymes, monoclonal antibodies), enzymes inhibitors, steroids, vaccines,
Energy	Ethanol (gasohol), methane (biogas), biomass
Food	Dairy products (cheeses, yogurts, fish and meat products), beverages (alcohol, tea and coffee), baker's yeast, food additives (antioxidants, colors, flavors, stabilizers), novel foods (soy sauce, tempeh, miso), mushroom products, amino acids, vitamins, starch products, glucose and high fructose syrups, functional modifications of proteins, pectins
Agriculture	animal feedstuffs (single cell protein), veterinary vaccines, ensilage and composting processes, microbial pesticides, Rhizobium and other N-fixing bacterial inoculants, mycorrhizal inoculants, plant cell and tissue culture (vegetative propagation, embryo production, genetic improvement)

Source: Smith (1996)

a: organic chemicals (bulk), b: organic chemicals (fine), c: inorganic chemicals

Table 3. Companies commercializing biotechnology in the US and their product markets. (As of March 1983)[23]

company (year established)	commercial application of R&D
Abbot Laboratories	Ph
Actagen (1982)	Ph
Advanced Biotechnology Associates, Inc. (1981)	Ph
Advanced Genetic Sciences, Inc. (1979)	PA
Advanced Genetic Research Institute (1981)	AA
Advanced Mineral Technologies, Inc. (1982)	Env
Agrigenetics Corp. (1975)	PA, SCF
Allied Chemical Corp.	PA
Alpha Therapeutic Corp.	Ph
Ambico, Inc. (1974)	AA
American Cyanamid Co.	Ph, PA, AA
American Diagnostics Corp. (1979)	Ph
American Qualex (1981)	Ph, AA
Amgen (1980)	Ph, PA, AA, SCF
Angenics (1980)	Ph
Animal Vaccine Research Corp. (1982)	AA
Antibodies, Inc. (1960	Ph, AA
Applied DNA Systems, Inc. (1982)	Ph, SCF, CCE, Env
Applied Genetics, Inc. (1981)	AA
ARCO Plant Cell Research Institute	PA
Atlantic Antibodies (1973)	AA
Axonics	Ph
Baxter-Travenol Laboratories, Inc.	Ph
Becton Dickinson & Co.	Ph
Bethesda research Laboratories, Inc. (1976)	Ph, AA
Biocell Technology Corp. (1980)	Ph
Biochem Technology, Inc. (1977)	Bioprocessing
Bio-con, Inc. (1971)	AA
BioGenex laboratories (1981)	Ph
Biogen, Inc. (1980)	Ph, AA, CCE, Env
Biological Energy Corp. (1981)	CCE, SCF
Bio Response Inc. (1972)	Mass cell culture
Biotech Research Laboratories, Inc. (1973)	Ph, CCE
Biotechnica International, Inc.(1981)	PA, CCE, SCF, Env, AA, Ph
Biotechnology General Corp. (1980)	PA, AA, Ph
Brain Research (1968)	Ph

[23] Ph: Pharmaceutical, PA: Plant Agriculture, AA: Animal Agriculture, SCF: Specialty chemicals and food, CCE Commodity chemicals and energy, Env: Environmental (Microbial enhanced oil recovery, microbial mining, pollution control, and toxic waste treatment), El: Electronics

Bristol Myers Co.	Ph
BTC diagnostic, Inc. (1980)	Ph
Calgene, Inc. (1980)	PA
California Biotechnology, Inc. (1982)	Ph, AA
Cambridge Bioscience, Inc. (1982)	Ph, AA
Campbell Institute for Research and Technology	PA
Celanese Corp.	CCE
Cellorgan International, Inc. (1972)	Ph
Celtek, Inc. (1980)	Ph
Centaur Genetics Corp. (1981)	Ph, PA, AA
Centocor (1979)	Ph
Cetus Corp. (1971)	Ph, AA, CCE
CC- Madison (1981)	PA
CC- Palo Alto (1980)	Ph
CC-Immune (1980)	Ph
Chiron Corp. (1981)	Ph, AA
Ciba Geigy	Ph
Clonal Research (1970)	Ph
Codeine (1980)	CCE
Collaborative Genetics, Inc. (1979)	Ph, SCF, CCE
Collagen, Inc. (1977)	Ph
Cooper Diagnostics, Inc.	Ph
Cooper-Lipotech, Inc. (1981)	Ph
Corning Glass Works	SCF
Crop Genetics International (1981)	PA
Cutter Laboratories, Inc.	Ph
Cytogen Corp. (1981)	Ph
Cytox Corp. (1975)	Env
Damon Biotech, Inc. (1981)	Ph
Dairyland Foods Corp.	SCF
Dart and Kraft, Inc.	SCF
Davy Mckee Corp.	Bioprocessing
DeKalb Pfizer Genetics (1982)	AA
Diagnon Corp. (1981)	Ph
Diagnostic Technology, Inc. (1980)	Ph
Diamond Laboratories	AA
Diamond Shamrock Corp.	AA, CCE
DNA Plant Technology (1981)	PA
DNAX Corp.	Ph
Dow Chemical Co.	Ph, PA, CCE, SCF, AA, Env
Ean-tech, Inc. (1982)	El, Env, Ph
Eastman Kodak Co.	Ph, Env
Ecogen (1983)	PA
E.I. du Pont de Nemours & Co., Inc.	Ph, PA, CCE, SCF
Electro Nucleonics Laboratories, Inc.	Ph
Eli Lilly & Co.	Ph, PA
EnBio, Inc. (1975)	Bioprocessing

Endorphin, Inc. (1982)	Ph
Engenics, Inc. (1981)	Bioprocessing
Enzo Biochem, Inc. (1976)	Ph, AA, CCE, SCF, PA
Enzyme Bio-systems, Ltd.	SCF
Enzyme Center, Inc.	SCF
Enzyme Technology Corp.	SCF
Ethyl Corp.	CCE, SCF, Env
Exxon Research & Engineering Co.	CCE, Env, SCF
Fermentec Corp. (1978)	Bioprocessing
FMC Corp.	Ph
Frito- Lay, Inc.	PA
Fungal Genetics, Inc. (1982)	Ph, SCF
Genencor (1982)	SCF, CCE
Genectech, Inc. (1976)	Ph, AA, CCE, El
General Electric Co.	El, Env, Ph, SCF
General Foods Corp.	PA
General Genetics (1982)	Ph
General Molecular Applications (1981)	Ph
Genetic Diagnostic Corp. (1981)	Ph
Genetic Replication technologies, Inc. (1980)	Ph, AA
Genetic Systems Corp. (1980)	Ph
Genetics Institute (1980)	Ph, PA, SCF, Env
Genetics International, Inc. (1980)	AA, Ph, SCF, CCE, Env, El
Genex Corp. (1977)	Ph, AA, SCF, Env
Gentronix laboratories, Inc. (1972)	El
Genzyme (1981)	SCF
W.R. Grace & Co.	AA, SCF, Env, PA, Ph
Hana Biologics, Inc. (1978)	Ph
Hem Research (1966)	Ph, AA
Hoffman-La-Roche Inc.	Ph
Hybridoma Sciences, Inc. (1981)	Ph
Hybritech, Inc. (1978)	Ph
Hytech Biomedical, Inc. (1981)	El, Ph
IBM Corp.	El
IGI Biotechnology, Inc. (1975)	Ph
Immulok, Inc. (1980)	Ph
Immunetech, Inc. (1981)	Ph
Immunex Corp. (1981)	Ph
Immuno Modulators Laboratories, Inc. (1982)	Ph
Immunogen (1981)	Ph
Immunotech Corp. (1980)	Ph
Imreg, Inc.	Ph
Indiana BioLab (1972)	PA, AA, SCF, CCE
Integrated Genetics, Inc. (1981)	Ph
Interferon Sciences, Inc. (1980)	Ph
International Genetic Engineering, Inc. (Ingene) (1980)	Ph, PA, CCE

International Genetic Sciences Partnership (1981)	PA, AA
International Minerals & Chemical Corp.	AA, PA, Env, CCE
International Plant Research Institute (IPRI) (1978)	PA
Kallestad laboratories, Inc.	Ph
Kennecott Copper Corp.	Env
Lederie Laboratories	Ph, AA
The Liposome Co., Inc. (1981)	Ph, AA
Liposome Technology, Inc. (1981)	Ph, AA
Litton Bionetics	Ph
3M Co.	Ph
Mallinckrodt, Inc.	Ph
Martin Marietta	SCF, PA
Meloy Laboratories, Inc. (1975)	Ph
Merck & Company, Inc.	Ph, AA
Microlife Genetics (1981)	SCF, Env
Miles Laboratories	Ph, SCF, CCE, AA
Miller Brewing Co.	PA
Molecular Biosystems, Inc. (1980)	Ph
Molecular Diagnostics (1981)	Ph
Molecular Genetics, Inc. (1979)	Ph, PA, AA
Molecular Antibodies, Inc. (1979)	Ph, AA
Monsanto Co.	PA, AA
Multivac, Inc.	Ph, PA, AA, SCF
Nabisco, Inc.	PA
National Distillers & Chemical Co.	CCE
NPI (1973)	PA,CCE, SCF
Neogen Corp. (1981)	PA, AA
New England Biolabs	Ph
New England Monoclonal Resources (1982)	Ph
New England Nuclear Corp.	Ph
Norden Laboratories	AA
Novo Laboratories, Inc.	Ph, SCF
Nuclear & Genetic technology, Inc. (1980)	Ph
Ocean Genetics (1981)	SCF
Oncogen (1982)	Ph
Oncogene Science, Inc. (1983)	Ph
Organon, Inc.	Ph
Ortho Pharmaceutical Corp.	Ph
Petrogen, Inc. (1980)	Env
Pfizer, Inc.	Ph, PA, CCE, AA, SCF, Env
Phillips Petroleum Co.	Env, SCF, CCE
Phytogen (1980)	PA
Phyto-Tech Lab	PA
Pioneer Hybrid International Corp.	PA
Plant Genetics, Inc. (1981)	PA

Polybac Corp.	Ph, SCF, Env
PPG Industries	SCF
Purification Engineering, Inc.	Bioprocessing
Quidel Home (1982)	Ph
Replicon (1982)	Ph, SCF
Repligen Corp. (1981)	Ph, AA, CCE, SCF
Ribi Immunochem Research, Inc. (1981)	AA, Ph
Rohm & Haas	PA
Salk Institute Biotechnology/Industrial Associates, Inc. (1981)	Ph, AA, CCE
Sandoz, Inc.	Ph, PA, AA
Schering-Plough Corp.	Ph, AA
SDS Biotech Corp. (1983)	AA
G.D. Searle & Co.	Ph, SCF
Serono laboratories, Inc.	Ph
SmithKline Beckman	Ph, AA
E. R. Squibb & Sons, Inc.	Ph
A. E. Staley Manufacturing Co.	AA, PA, SCF
Standard oil of California	Emv
Standard Oil of Indiana	Ph, PA
Standard Oil of Ohio	PA
Stauffer Chemical Co.	PA
Summa Medical Corp.	Ph
Sungene Technologies Corp. (1981)	PA
Sybron Biochemical	Env
Synbiotex Corp. (1982)	Ph, AA
Syncor International	Ph
Synergen (1981)	AA, SCF, CCE, Env
Syngene Products and Research, Inc.	AA
Syntex Corp.	Ph, AA
Syntro Corp. (1982)	AA, CCE
Syva Co. (1966)	Ph
Techniclone International Corp. (1982)	Ph
Unigene Laboratories, Inc. (1980)	Ph, AA
Universal Foods Corp.	SCF, PA
University Genetics Co. (Genetics Clinics) (1980)	Ph
U.O.P., Inc.	SCF, CCE
The Upjohn Co.	Ph, AA, PA
Viral Genetics (1981)	Ph
Wellcome Research Laboratories	Ph
Worne Biotechnology, Inc. (1982)	PA, CCE, Ph, AA, Env, SCF
Xenogen, Inc. (1981)	Ph, PA
Xoma Corp. (1981)	Ph
Zeocon Corp. (1968)	PA, AA
Zymed laboratories	SCF, CCE
Zymos Corp. (1982)	Ph, SCF

Source: Office of Technology Assessment (1984)

Table 4. Japanese entrants in biotechnology-based pharmaceuticals

Entrant's main field	*pharmaceutical field of entry*
Chemical companies	
Chisso	Diagnostic reagents
Daicel	anticancer drugs
Denki Kagaku Kogyo	physiologically active agents
Hitachi Chemical	Antibiotics, vaccines
Hokko Chemical Industry	Antibiotics
Mitsubishi chemical industries	Physiologically active agents, anticancer drugs, diagnostic reagents, monoclonal antibodies.
Mitsubishi petro-chemical industries	Diagnostic reagents
Mitsui Toatsu chemical	Urokinase
Sumitomo chemicals	monoclonal antibodies, interferon, growth hormone
Sunstar	antibiotics, interferon
Food Processing companies	
Ajinomoto	antibiotics, production of amino acids, R&D into anti cancer substances and immunomodulators)
Kikkoman Shoyu	physiologically active agents, antibiotics, immune suppressers, R&D on enzymes, diagnostics drugs
Kirin Brewery	anticancer drugs
Kirin Seagrams	interferon
Kyowa hakko	physiologically active agents, interferon, amino acids, anti cancer (γINF, tPA)
Meiji Milk products	Physiologically active agents, interferon
Meiji Seika Kaisha	antibiotics, interferon
Sanraku-Ocean	Antibiotics
Sapporo Breweries	Anticancer drugs
Snow brands	anti-cancer agents,
Suntory	antibiotics, interferon, anticancer drugs, drugs for treatment of high blood pressure
Takara Shuzo	Physiologically active agents
Toyo Jozo	Immune suppressers (Alcoholic beverages, pharmaceuticals, R&D into immunosuppressants)
Yakult Honsha	Physiologically active agents anticancer drugs, diagnostic reagents for liver cancer
Textile and pulp companies	
Asahi chemical industry	interferon
Toray industries	interferon
Teijin Limited	interferon

Kirin Seagrams	interferon

Source: Daly (1985).

Table 5. Contractual R&D: alliances and agreements between them [24]

Large firms	*Contract agreements*
Biogen N.V	
Monsanto	Monsanto will fund Biogen's developments of a techniques to produce Biogen's tissue plasminogen activator.
INCO	INCO has a contract with Biogen to do studies of the feasibility of bioextraction of nonferrous metals from low grade ores and other sources of minerals
Suntory	Suntory has an agreement under which Biogen will develop rDNA to produce tumor necrosis factor, to scale up production, and to support clinical trials, and Suntory will have exclusive marketing rights in Japan and Taiwan.
Calgene	
Rhone-Poulenc	Calgene has a research contract to develop new herbicide resistant varieties of sunflower for Rhone-Poulenc
Allied chemical corp.	ACC has a contract with Calgene under which Calgene will do research in nutrient efficiency in plants
Cetus	
Roussel Uclaf	RU has a contract under which Cetus produces vitamin B12.Cetus is receiving royalties.
TechAmerica	TechAmerica has a contract under which Cetus will develop a rDNA antigen to be used as a vaccine against calf bovine diarrhea. TechAmerica will perform clinical research, manufacture and market
Norden Labs	NL has a contract with Cetus under which Norden will produce and market rDNA colibacillosis vaccine. Cetus receives royalties.
Shell Oil Co.	SOC gave a contract to Cetus under which Cetus will develop human beta-l (fibroblast) interferon.
Collaborative Genetics	
Akzo N.V.	ANV gave a research contract to CG to develop genetically manipulated micro-organisms to produce bovine growth hormone.
Dow	Dow has given a research contract to CG under which CG will produce rennin via genetically manipulated micro-organisms
Damon Biotech	
Hoffmann-La Roche	HLR has contracted Damon to apply its microencapsulation system to the production of Mabs. LHR will retain the marketing rights to the interferon produced by this process.
Genentech	

[24] A firm indicated by a bold letter is a small research firm and those under that are a large firm.

Boehringer Ingelheim (BI)	Agreement providing BI with exclusive marketing outside USA for Genentech's tissue-type plasminogen activator. Genentech receives contract revenues and bulk sales/royalty revenues. BI has marketing right in Europe for Gannett's gamma interferon
Kabi GenAB	Agreement provides Kabi with world-wide rights to produce and market human growth hormone currently undergone clinical trial testing. Genentech has right to supply a percentage of Kabi's need and retains right to market product in US and Canada
Kyowa-Hakko	Agreement to produce and market tissue plasminogen activator thrombus dissolving agents in Japan
Hoffmann-La Roche	Genentech has a joint development contract with HLR for the production of leukocyte and fibroblast interferons. HLR will conduct testing its effectiveness. Genentech will supply part of Roche's requirements and receive royalties on sales.
Genetic Systems Corp.	
Cutter Labs	Cutter labs and GS have a $2.5 millions joint venture to develop human Mabs for the diagnosis and treatment of Pseudomonas infections. For other MAB products, GS will do R&D and market the diagnostic products and Cutter will market therapeutic products.
Syva	Syva has a research, development and marketing agreement with GS which will finance some of GS's R&D activities related to diagnostic tests for sexually transmitted diseases such as herpes, gonorrhea, and chlamydia. GS receives 5% royalties on sales.
Genetics Institutes	
Sandoz	Sandoz is funding research by Genetics institutes to clone monokines and lymphokines in bacteria, i.e., interleukin-2
Genex	
Green Cross	A contract for the production of human serum albumin and Kabi GenAB using Genex's rDNA technology.
Mitsui Toatsu	a contract to develop human urokinase using rDNA technology.
Schering AG	2 research contracts. The first one is development of an rDNA product to treat heart decease. The second one is that Genex is to improve a rDNA strain for amino acid production and develop process technology for scale-up processes.
Yoshitomi Pharmaceutical	a contract to develop a rDNA strain to produce human interleukin-2.
Bristol-Myers	BM has a contract with Genex under which Genex will develop genetically modified micro-organisms that will produce leukocyte (alpha) and fibroblast (beta) interferons, BM owns all rights. Genex receives royalties.
A Japanese company	A Japanese company (proprietary) has a contract with Genex under which Genex will develop a genetically modified micro-organisms to produce L-tryptophan, All discoveries will be the sole properties of the Japanese customer.

Koppers	Koppers has a contract with Genex under which Genex will develop genetically modified micro-organisms to do biocatalytic transformations of aromatic chemicals from coal distillate derivatives. All micro-organisms and research findings are the sole properties of Koppers. Genex will receives royalties
Schering AG	SAG has a contract with Genex under which Genex will develop a microbe that will produce a blood plasma protein. SAG will receive world-wide exclusive licenses.
Green Cross	GC has a contract under which Genex will develop a microbial strain that produces human serum albumin (HAS). GC will receive exclusive license to sell for at least 15 years, all microbially produced HAS under the contract in Japan, South-East Asia, India, China, Australia, New Zealand, North America, and South America. Genex receives Royalties.
KabiVitrum	KabiVitrum has a contract with Genex for HAS similar to that of Green Cross except Kabi's rights are limited to Africa, Europe, and the Middle East.
Yoshitomi Pharmaceutical Industries	YPI has a contract with Genex under which Genex will develop genetically modified micro-organisms to produce interleukin-2.
Mitsui Toatsu Chemicals Inc.	MTC has contracted Genex to develop a microbial strain that produces human urokinase. Genex will retain the patent and MTC will receive an exclusive license with the right to make, use, and sell the product for the royalty period, about 15 years.
Pharmacy	Pharmacy has a contract with Genex under which Genex will develop a nonpathogenic strain of bacteria that would produce a protein with potential therapeutic applications.
Hanna Biologics Inc.	
Recordati S.p.A	RS.p.A has an agreement with Hana under which Hana will develop and distribute biomedical research and MAbs diagnostic products.
Fujizoki pharmaceutical Co.	FP has a joint venture with Hana under which Hana will develop new immunodiagnostic tests. Also Fujizoki has a distribution agreement with Hana under which Fujizoki will market Hana products in Japan.
Hybritech	
Teijin	Teijin provides $ 7.5 millions over three year periods to develop human monoclonal antibodies. Teijin gets rights of marketing in the Far East and Hybritech in North America and sharing the right in the rest of the parts. Hybritech gets access to Teijin's proprietary immunochemistry methods.
Teijin	Teijin has an agreement with Hybritech under which Hybritech will develop human Mabs for treatment of lung, breast, colorectal, and certain leukemia-lymphoma type cancers. The goal of the joint venture is to combine Hybritech 's MAb manufacturing technique and Teijin's unique technique of binding a cytotoxic substance to an antibody for cancer therapy.

Travenol laboratories Inc.	TL will provide $ 1 million for research and $ 1.9 million for stepwise benchmark payment to Hybritech to develop MAbs for treating major bacterial infections. Hybritech will receives royalties on Travenol's worldwide sales.
Interferon Sciences	
Green Cross	GC has a $ 2.5 million R&D and supply agreement with IS under which IS will supply GC with gamma and alpha interferon.
Molecular Genetics	
American Cyanamid	AC has an R&D contract and licensing agreement with MG under which MG will develop bovine growth hormone Cyanamid is conducting scale-up and testing
American Cyanamid	(1) AC has an R&D contract and licensing agreement with MG under which MG will develop bovine growth hormone. AC is conducting scale-up and clinical trial. (2) AC sponsored an R&D contract and formed a licensing agreement with MG to select herbicide resistant corn in tissue culture.(3) AC sponsored an R&D contract and formed a licensing agreement with MG under which AC will conduct human testing, secure regulatory approvals, and manufacture and market ant products developed from MG's human herpes simplex vaccine research. *Lederie* has begun pre-clinical testing.
Phillips Roxane	PR sponsored research and has exclusive license to manufacture and market bovine papilloma virus vaccine developed by MG. PR is responsible for obtaining government approval.
Monoclonal Antibodies	
Oath Pharmaceuticals	OP has an agreement with MA under which MA will develop and manufacture an innovate diagnostic product that will be marketed by OP.
Zymos Inc.	
Cooper Laboratories	CL funded research and has the rights to alpha-1 anti trypsin developed by Zymos for possible treatment in emphysema.

Source: Office of Technology Assessment (1984)

Appendix B. Glossary of technical terms

- **Amino Acids** Organic acids which constitutes the building blocks of proteins. They are produced industrially for use in food, feed and pharmaceutical industries.
- **Antibodies** A protein produced by living organisms in response to a foreign agent or antigen.
- **Antigen** A protein or other molecules which when generated into a human or animal body will generate the production of an antibody.
- **Assay** A technique that measures a biological response.
- **Biomass** All organic matter that grows by the photosynthetic conversion of the solar energy
- **Calcitonin** A small peptide hormone produced by the thyroid which regulates calcium transport and uptake
- **Colibacillosis** A bacterial diseases that causes diarrhea, dehydration, and death in calves and piglets.
- **Commodity chemicals** Chemicals produced in large volumes that sell for less than $1 per pound
- **DNA** Deoxyribonucleic acid. The chemical out of which genes are made.
- **Diagnostics (*in vitro*)** Diagnostics kits and systems for use on tissue or fluid samples in the laboratory. Included here are tests which have been available for some time and also some new tests incorporating monoclonal antibodies.
- **Diagnostics (*in vivo*)** Diagnostic technology for use within the body such as monoclonal antibody-based visualization of cancer cells.

- **Enzyme** A protein which acts as a catalyst in biological reaction.
- **Factor VIII** A protein involved in blood clotting which is used in the therapy for hemophilia.
- **Fermentation** A process which uses living micro-organisms (or their products) to cause a desired chemical transformation of a particular substance.
- **Gene** The fundamental unit of heredity. It is composed of the chemical DNA and the information contained in its structure is used in the cell to direct the production of a particular protein.
- **Genetic engineering** (also recombinant DNA or rDNA) The construction and manipulation of hybrid DNA to introduce genes coding for desired proteins into specific organisms.
- **Growth hormone** A peptide involved in the regulation of growth.
- **Herbicide** An agents (e.g. s chemical) used to destroy or inhibit plant growth; specifically, a selective weed killer that is not injurious to crop plants.
- **Human serum albumin** the major protein component of human plasma. It is used medically for treating shock, burns and in some types of surgery.
- **Immunomodulator** A class of substances which regulate the activity of the immune response.
- **Immunosuppressant** A class of substances which cause suppression of the immune response.
- **Interferons** A class of immune regulators or lymphokines which are involved in the responses of cells to viral infection and cancer. There are three subgroups, alpha, beta and gamma interferons. They have received much attention as future anticancer agents.

- **Interleukin-2** A type of immunomodulator which is being tested for anti-cancer effects. It stimulates T cell growth *in vivo*.
- **Lymphocytes** White blood cells involved in the immune response. There are two main types. B lymphocytes (B cells) and T lymphocytes (T cells). The former produces antibodies and the latter are involved in cell mediated immunity and in helping B cells.
- **Lymphokines** A class of immunoregulators produced by lymphocytes.
- **Macrophage activating factor** A lymphokines released from T cells and causing activation of macrophages. It is being investigated for possible anti-cancer effects.
- **Metabolism** The physical and chemical processes by which foodstuffs are synthesized into complex substances are transformed into simple ones, and energy is made available for use by an organism.
- **Microencapsulation** The process of surrounding cells with a permeable membrane
- **Monoclonal antibody (MAbs)** A highly specific type of antibody produced by a single clone of cells which can recognize only one antigenic site.
- **Peptide** A short segment of protein.
- **pH** A measure of the acidity or basicity of a solution on a scale of 0 (acid) to 14 (basic). For example, lemon juice has a pH of 2.2 (acid), water has a pH 7 (neutral), and a solution of baking soda has a pH of 8.5 (basic).
- **Photosynthesis** The reaction carried out by plants where carbon dioxide from the atmosphere is fixed into sugar in the presence of sunlight; the transformation of solar energy into biological energy.
- **Plasma** The liquid (noncellular) fraction of blood. In vertebrates, it contains

many important proteins (e.g. fibrinogen, responsible for clotting).

- **Plasmid** A small loop of extrachromosomal DNA used as a vector in recombinant DNA research.
- **Polypeptide** A long peptide, which consists of amino acids.
- **Protein** A polypeptide consisting of amino acids. In their biologically active states, proteins function as catalysts in metabolism and, to some extent, as structural elements of cells and tissues.
- **Reagents** A substance that takes part in a chemical reaction
- **Specialty chemicals** Chemicals, which usually produced in small volumes, that sell for more than $1 per pound.
- **Tissue plasminogen activator** A substance which causes activation of plasmid which is involved in the breakdown of blood clots.
- **Tumor necrosis factor** A macrophage produced protein which exhibits *in vitro* and *in vivo* killing of tumor cells. It has about 30 percent homology of amino acid sequences with lymphotoxin.
- **Urokinase** A thrombolytic enzyme involved in breakdown of blood clots. It occurs in human urine.
- **Vector** In recombinant DNA research it refers to any piece of DNA such as a plasmid, phage or virus which can be used to introduce new genes into a cell.

Chapter 3. Overview of the literature on research joint ventures with spillovers.

1. Introduction

It is said that various externalities cause market failure in the market for innovation. Geroski (1993) mentions three types of externality: information spillovers, pecuniary externalities, and environmental externalities. Spillover externalities arise when information generated by a firm leaks to its competitors, and the externalities are a positive one. Pecuniary externalities arise when the actions of a firm directly affects the cost or demand of its competitors, or their actions in R&D. For instance, risk sharing or cost sharing among firms are regarded as positive externalities. On the other hand, R&D by a firm, which gives it an advantage over its competitors in market competition and, subsequently, retards their R&D investment, is a negative externality. Environment externalities arise when the action of a firm affects the expectation or attitude of its competitors in a way which affects how they react to the firm's action. For instance, if a firm cooperates in R&D with its competitors, that could affect the pricing decision by the competitors. This sort of externalities can be positive or negative, depending on circumstances.

Several methods have been proposed to alleviate this market failure. R&D subsidies are used to raise expected returns of firms by lowering their costs of doing R&D. Patents enable firms to appropriate some of the rents resulting from its R&D output and, thus, restore their incentive to invest in R&D.

Since the late 80s, it has been argued that Research Joint Ventures (RJVs hereafter) could be used as an institutional mechanism to mitigate market failure. The rationale is that in RJVs competing (or non-competing) firms cooperate in

R&D, which enables them to internalize various externalities. This is said to induce firms to expand their R&D investment.

Since the papers by Katz (1986) and above all D'Aspremont and Jacquemin (1988) (D&J hereafter), many papers have investigated when or whether RJVs induce more R&D investment from firms than non-cooperative R&D where firms conduct R&D non-cooperatively.

This chapter provides an overview of some key papers in the literature of RJVs with spillovers. I begin with the paper by D&J and then show its extensions. After mentioning criticisms made to the papers, I will explain in what way they are related to my analysis of R&D organization.

2. D'Aspremont and Jacquemin

D &J consider the following situation. In an industry, firm *1* and *2* conduct R&D to reduce their marginal production cost. [25] Then they compete *á la* Cournot in a final good market, and firm *1* earn profits, $\pi_1 = \pi(c_1, c_2)$, where c_i $(i = 1, 2)$ is the post-R&D marginal cost of firm *i* and

$$\text{(i) } \partial\pi_1/\partial c_1 < 0 \text{, (ii) } \partial\pi_1/\partial c_2 \geq 0 \text{, (iii) } \left|\partial\pi_1/\partial c_1\big|_{c_1=c_2}\right| \geq \left|\partial\pi_1/\partial c_2\big|_{c_1=c_2}\right|. \qquad \text{(3-1)}$$

[25] In what follows, I use the assumption in the literature that both firms are identical. Thus everything that I say about firm *1* applies to firm *2* too (by swapping *1* with *2* (in subscripts)) and, unless necessary, I will mention only firm *1*.

(i) says that firm *1* can benefit from the lower marginal cost while (ii) indicates that if firm *2* lowers its cost, it adversely affects profits of firm *1*.[26] However (iii) suggests that the former effect is larger than the latter if $c_1 = c_2$.

Anticipating them, firms decide the level of their R&D investment. Let x_1 be the *notional* R&D investment by firm *1*.[27] This generates the information, $f(x_1)$, which can be used for its R&D. As I said earlier, the information which a firm produces can leak out to its competitor. Let $\phi f(x_2)$ be the information or spillover, which firm *1* gets from firm *2* that way. ϕ is the rate of information leakage across firms where $\phi \in [0,1]$. This definition implies the followings; (i) such information leakage is assumed to be involuntary, and, thus, only a fraction, ϕ, of the information of firm *2* spills over to firm *1*; (ii) a larger ϕ means a larger information leakage to firm *1* from firm *2*. Thus, the aggregate amount of information which firm *1* utilizes for its R&D or its *effective* R&D investment is defined as

$$z_1 = f(x_1) + \phi f(x_2). \tag{3-2}$$

For simplicity, it is usually assumed in the literature that $f(x_i) = x_i$.

The R&D effective investment is assumed to have a deterministic relationship with its production marginal cost, i.e. $c_1 = c(z_1)$. The usual assumption in the literature is

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[26] Only if both firms operate in two *independent* markets, does (ii) hold with equality.

[27] This represents, say, new equipment and hiring or training staffs associated with its research project. In what follows, I refer to this just as R&D investment.

$$dc_1/dz_1 < 0 \leq d^2c_1/d(z_1)^2 \ \forall \ z_1 \geq 0 \qquad (3\text{-}3)$$

That is, the more effective investment leads to the lower marginal cost. Using (1) and (3), I define

$$A_1 = (\partial\pi_1/\partial c_1)(dc_1/dz_1) > 0 \quad \text{and} \quad B_1 = (\partial\pi_1/\partial c_2)(dc_2/dz_2) \leq 0. \qquad (3\text{-}4)$$

As I said earlier, the main objective of the literature is to examine whether RJVs can result in more R&D investment than non-cooperative R&D and, thus, mitigate market failure. The literature usually does that by comparing the equilibrium level of R&D investment in two cases. In the standard case, assuming that firm *2* behaves optimally, firm *1* solves in non-cooperative R&D and RJVs

$$\underset{x_1}{Max}\ \Pi_1 = \pi(c_1(z_1), c_2(z_2)) - x_1. \qquad (3\text{-}5)$$

$$\underset{x_1}{Max}\ T = \sum_{i=1}^{2} \Pi_i. \qquad (3\text{-}6)$$

respectively. In the former (latter) firm *1* maximizes its own (joint) profits. Thus

$$\partial\Pi_1/\partial x_1 = A_1 + \phi B_1 - 1 = 0. \qquad (3\text{-}7)$$

$$\partial T/\partial x_1 = A_1 + \phi B_1 + B_2 + \phi A_2 - 1 = 0.^{28} \qquad (3\text{-}8)$$

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[28] Here, B_2 and ϕA_2 are pecuniary externalities and spillovers externalities which I mentioned earlier.

Using (3-7) and (3-8), I can examine whether RJVs induce more R&D investment by firms than non-cooperative R&D. At first, to simplify the analysis, let us impose the symmetry conditions on (3-7) and (3-8), and define x^N and x^{RI} as the solution for them respectively. Then I get

$$\partial \Pi / \partial x \big|_{x=x^N} = A + \phi B - 1 = 0 \tag{3-9}$$

$$\partial T / \partial x \big|_{x=x^{RI}} = (1+\phi)(A+B) - 1 = 0 \tag{3-10}$$

Then, evaluating (3-9) at x^{RI} and using (3-10), I get

$$\partial \Pi / \partial x \big|_{x=x^{RI}} = -(\underbrace{\phi A}_{+} + \underbrace{B}_{-}) . \tag{3-11}$$

In a symmetric equilibrium, $dc_1/dz_1 = dc_2/dz_2$. This and (1)-(iii) imply that

$$|A| \geq |B|. \tag{3-12}$$

(3-12) means that (3-11) will be positive (negative) if ϕ is small (large). Thus

Result 3-1. $x^N > x^{R1}$ *iff* ϕ *is small.*

The intuition is as follows. Comparison of (3-7) with (3-8) shows that firm *1*

internalizes two externalities in RJVs. B_2 is the rent shifting externality, which illustrate rent shifting (in a final good market) from firm *2* to firm *1* due to cost reduction of firm *1*. This has a negative impact on joint profits. ϕA_2 is the spillover externality, which is the efficiency gain for firm *2* resulting from its lower marginal cost *via information leaking out of firm 1 to firm 2*. [29] This has a positive impact on joint profits. When ϕ is small, the former outweighs the latter so that firm *1* essentially internalizes *negative* externalities in RJVs. Thus, it cuts back its R&D investment. When ϕ is large, the latter dominates the former so that firm *1* basically internalizes *positive* externalities. This induces it to expand its R&D investment.

3. Extensions

Suzumura (1992) generalizes the demand function and the marginal cost function in D&J and assumes a n firm case where $n \geq 2$. These extensions turned out not to alter the above results and their intuition. [30]

Kamien *et al* (1992) extended RJVs in D&J by considering three scenarios of cooperation in RJVs: coordination in R&D investment as above (R&D

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[29] Strictly speaking, B_2 and ϕA_2 are more than rent shifting and the efficiency gain respectively. For instance, suppose that firms compete *á la* Cournot in a final good market. If c_1 goes down via the large z_1 in B_2, the output level of firm *1* goes up while that of firm *2* goes down. The former change results in rent shifting from firm *1* to firm *2* but the latter affects only profits of firm *2* and has nothing to do with rent shifting. A similar argument applies to ϕA_2 as well.

[30] His main finding is that, in spite of the presence of spillovers, non-cooperative R&D would result in more R&D investment than the socially second best level if ϕ is small and $n \geq 3$. (Though he examined a case of no spillovers, this result holds for non-zero spillovers as long as they are small).

cartelization); full information sharing by firms (i.e. $\phi = 1$ in the above case) (RJV competition); both (RJV cartelization). Together with extension to oligopoly and incorporation of product differentiation, they examine the level of R&D investment in non-cooperative R&D and these three cases of RJVs.

They find that the third case of cooperation will lead to the largest R&D investment while the second yields the smallest. I can find the logic of these results by using (3-7) and (3-8). In the former case (3-8) says that firms internalize very strong positive externalities when $\phi = 1$. On the contrary, in the latter case (3-7) shows that the negative impact, ϕB_1, on the profits is quite strong when $\phi = 1$, which severely discourages firms to invest in R&D.

R&D cartelization induces more R&D investment than non-cooperative R&D if, given ϕ, products are significantly differentiated. Otherwise the result is reversed. I see the logic of the arguments by referring to B. Now let $\rho = B/A$ (≤ 0). Note that, given z_1 and z_2, the more products are differentiated, the smaller $\partial \pi_1 / \partial z_2$ in B is and, thus, the larger ρ is. Substituting ρ into (3-11), I get

$$\partial \Pi / \partial x \Big|_{x=x^{R1}} = \underbrace{-}_{-} \underbrace{A(\phi + \rho)}_{?}. \qquad (3\text{-}13)$$

Result 3-2. $x^N \geq x^{R1}$ *iff* $(\phi + \rho) \leq 0$ *where equality holds if* $\phi + \rho = 0$.

Defining α ($\in [0,1]$) as the rate of differentiation between a product of one firm and that of the other, Kamien *et al* (1992) showed that $x^N \geq x^{R1}$ iff $2\phi \leq \alpha$ (where equality holds if $2\phi = \alpha$). [31]

[31] A large (small) α means less (more) differentiation in their model.

Vonortas (1994) modeled a three-stage game, two R&D stages and Cournot competition in the final stage. He set up two R&D stages to capture in his model the fact that in generic research there often takes place information leakage among firms while in a development stage there seldom does. In his model, firms engage in either non-cooperative R&D, R&D cartelization, or RJV cartelization in the first R&D stage in the presence of spillovers, as in Kamien *et al* (1992). In the second R&D stage, firms decide the level of their R&D investment non-cooperatively in the absence of any spillovers. The effective investment by firm *1* is defined as

$$z_1 = x_1 + \phi x_2 + y_1 \tag{3-14}$$

where x_1 and x_2 are R&D investment of firms in the first stage, and y_1 that of firm *1* in second stage.

Thus, in the second stage firm *1* solves

$$\underset{y_1}{Max}\ \Pi_1 = \pi(c_1(z_1), c_2(z_2)) - y_1 \tag{3-15}$$

where z_1 is given by (3-13). Thus, I get

$$\partial \Pi_1 / \partial y_1 = A_1 - 1 = 0\,. \tag{3-16}$$

In Vonortas (1994), (3-5) ensures that the increase in x_1 unambiguously raises A_1 in (3-16) whereas the increase in x_2 lowers A_1 iff ϕ is small. Thus, $\partial y_1 / \partial x_1 > 0$ and $\partial y_1 / \partial x_2 < (>) 0$ if ϕ is small (large).

Going back to the first stage, in non-cooperative R&D and RJVs firm *1* solves

$$\underset{x_1}{Max}\ \Pi_1 = \pi(c_1(z_1), c_2(z_2)) - x_1 - y_1. \tag{3-17}$$

$$\underset{x_1}{Max}\ T = \sum_{i=1}^{2} \Pi_i \tag{3-18}$$

respectively. [32] Thus, using (3-16), I get

$$\partial\Pi_1/\partial x_1 = A_1(\partial y_1/\partial x_1) + B_1[\phi + (\partial y_2/\partial x_1)] - (\partial y_1/\partial x_1) - 1 = 0. \tag{3-19}$$

$$\partial T/\partial x_1 = A_1(\partial y_1/\partial x_1) + B_1[\phi + (\partial y_2/\partial x_1)] - (\partial y_1/\partial x_1) - 1$$
$$+ B_2[1 + (\partial y_1/\partial x_1)] + A_2[\phi + (\partial y_2/\partial x_1)] - (\partial y_2/\partial x_1) = 0. \tag{3-20}$$

At first, let us examine non-cooperative R&D and R&D cartelization. (3-19) and (3-20) suggest that in the latter firm *1* internalizes externalities, which are represented in the bottom line of (3-20). The first term there is obviously negative. According to Vonortas (1994), the second and the third terms are negative iff ϕ is small. It turned out that iff ϕ is small, the negative effects would outweigh the other so that firm *1* internalizes negative externalities in R&D cartelization. This results in the larger R&D investment in non-cooperative R&D iff ϕ is small.

Note that iff ϕ is small, in non-cooperative R&D firm *1* externalizes *negative* externalities while it internalizes positive externalities in RJV cartelization. Thus, RJV cartelization leads to more R&D investment than non-cooperative R&D when

[32] The equilibrium value of y will be different in three cases. However, in order to focus on the equilibrium value of x in each case, I will ignore that.

ϕ is large. However, the comparison is somehow ambiguous when ϕ is small. Vonortas (1994) shows that externalization of negative externalities has a larger positive impact on R&D investment than internalization of positive externalities in RJV cartelization. Thus firm *1* invests more in non-cooperative R&D. [33]

Defining x^{RC} as the equilibrium level of investment in RJV cartelization, I get

Result 3-3. $x^N > x^{RC}$ *iff* ϕ *is small.*

Comparison between (3-9) and (3-19), and between (3-10) and (3-20) show how addition of another R&D stage complicates the analysis.[34] In deciding the level of their first stage R&D investment, firms need to think how their investment affects their profits directly and indirectly via the change in y_1 and y_2. Moreover, the way in which their own first-stage investment affects their rivals' second stage investment depends on the spillover rate.

Ziss (1995) extends the D&J model in that firms may cooperate at both the production stage and the first stage. Thus, he considers four scenarios; non-cooperation, cooperation in R&D only (i.e., RJVs), cooperation in the production stage only, and cooperation in both stages. Note that if firms cooperate in the production stage, they internalize rent shifting externalities there. Ziss shows how

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[33] To simplify the argument, I attributed all the results here entirely to ϕ. However, this is a very rough sketch, and, in fact, his results depend on the combination of several parameters.

[34] Note that Result 3 differs from Kamien *et al* (1992), who showed that $x^{RC} > x^N \ \forall \phi$. Probably, the additional R&D stage induces firms to expand their x^N relative to x^N of the Kamien case while it discourages them to contract their x^{RC} relative to x^{RC} of the Kamien case.

such internalization affects firms' decision about R&D investment. Using a simplified version of his model, I will provide an outline of his result. Suppose that firm *1* sets its variable v_1 (price or quantity) optimally in the second stage to maximize its objective function. Thus, defining $\pi_1 = \pi(v_1, v_2)$ as its profits in the second stage game, I get

$$\partial\pi_1(v_1, v_2) / \partial v_1 + \lambda(\partial\pi_2(v_1, v_2) / \partial v_1) = 0 . \tag{3-21}$$

where λ = 1 (0) if firms do (do not) cooperate in the production stage. If firm *1* engages in non-cooperative R&D, it solves

$$\underset{x_1}{Max} \;\; \Pi_1 = \pi\{v_1[c_1(z_1), c_2(z_2)], v_2[c_1(z_1), c_2(z_2)], c_1(z_1)\} - x_1 . \tag{3-22}$$

Then using (3-21), we can write the first-order condition for firm *1* as

$$\begin{aligned} \frac{\partial\Pi_1}{\partial x_1} &= \frac{\partial\pi_1}{\partial v_1}\frac{\partial v_1}{\partial c_1}\frac{dc_1}{dz_1} + \phi\frac{\partial\pi_1}{\partial v_1}\frac{\partial v_1}{\partial c_2}\frac{dc_2}{dz_2} + \frac{\partial\pi_1}{\partial v_2}\frac{\partial v_2}{\partial c_1}\frac{dc_1}{dz_1} + \phi\frac{\partial\pi_1}{\partial v_2}\frac{\partial v_2}{\partial c_2}\frac{dc_2}{dz_2} + \frac{\partial\pi_1}{\partial c_1}\frac{dc_1}{dz_1} - 1 \\ &= -\lambda\left(\frac{\partial\pi_2}{\partial v_1}\right)\left(\frac{\partial v_1}{\partial c_1} + \phi\frac{\partial v_1}{\partial c_2}\right)\left(\frac{dc}{dz}\right) + \frac{\partial\pi_1}{\partial v_2}\left(\frac{\partial v_2}{\partial c_1} + \phi\frac{\partial v_2}{\partial c_2}\right)\left(\frac{dc}{dz}\right) + \frac{\partial\pi_1}{\partial c_1}\frac{dc_1}{dz_1} - 1 = 0 \end{aligned} . \tag{3-23}$$

The first term in the bottom line of (3-23) represents the effect on R&D investment of externalities internalized in the production stage. If λ = 1, this term is positive (in the usual model with the constant marginal cost and a linear demand function). That is, if firms cooperate at the second stage, they effectively internalize positive externalities from the viewpoint of R&D investment. This intuitively implies that

cooperation at the second stage yields larger R&D investment than no cooperation at all in both stage.

Using a similar method, I can compare R&D investment in the full cooperation case with that under RJVs. If firms cooperate in R&D, firm *1* solves,

$$\underset{x_i}{Max}\ T = \sum_{i=1}^{2} \Pi_i \,. \tag{3-24}$$

Thus using (3-21), I obtain

$$\begin{aligned} \frac{\partial T}{\partial x_1} = &-\lambda\left(\frac{\partial \pi_2}{\partial v_1}\right)\left(\frac{\partial v_1}{\partial c_1} + \phi\frac{\partial v_1}{\partial c_2}\right)\left(\frac{dc}{dz}\right) + \frac{\partial \pi_1}{\partial v_2}\left(\frac{\partial v_2}{\partial c_1} + \phi\frac{\partial v_2}{\partial c_2}\right)\left(\frac{dc}{dz}\right) + \frac{\partial \pi_1}{\partial c_1}\frac{dc_1}{dz_1} - 1 \\ &-\lambda\left(\frac{\partial \pi_1}{\partial v_2}\right)\left(\frac{\partial v_2}{\partial c_1} + \phi\frac{\partial v_2}{\partial c_2}\right)\left(\frac{dc}{dz}\right) + \frac{\partial \pi_2}{\partial v_1}\left(\frac{\partial v_1}{\partial c_1} + \phi\frac{\partial v_1}{\partial c_2}\right)\left(\frac{dc}{dz}\right) + \phi\frac{\partial \pi_2}{\partial c_2}\frac{dc_2}{dz_2} = 0 \end{aligned} \,. \tag{3-25}$$

If I use the standard model of D&J, I can verify from (3-25) that in this case too, cooperation at the second stage means internalization of positive externalities. Thus, full-cooperation leads to the larger R&D investment than RJVs.

The comparison between the full cooperation case and the second stage cooperation case rests on whether in the former firms internalize positive or negative externalities at the first stage. These externalities are expressed in the bottom line of (3-25). The second and the third term on the L.H.S. are the externalities which firms internalize in RJVs. Section 2 suggests that they are *positive* externalities iff ϕ is large. Moreover the first term is always positive. Thus, if ϕ is large, firms internalize positive externalities in the full cooperation case. When ϕ is small, the outcome is ambiguous. I can check, however, that in the D&J

model externalities are negative for a small ϕ.

Let us define x^{FC} and x^{C} as the equilibrium level of R&D investment in the full cooperation case and the case of cooperation in the second stage only. Combining these two results and the above ones, I get

Result 3-5. If ϕ is small, then $x^{C} > max\{x^{N}, x^{FC}\} > min\{x^{N}, x^{FC}\} > x^{RI}$. If ϕ is large, then $x^{FC} > max\{x^{C}, x^{RI}\} > min\{x^{C}, x^{RI}\} > x^{N}$. [35]

Steurs (1995) extended the D&J framework to a two-industry case. The aim is to analyze the impact on R&D investment of intra-industry spillovers, i.e., within an industry, and of inter-industry spillovers, i.e., across industries. He assumes two *independent* industries and that two firms operate in each of them. Firm *1* earns $\pi_{1k} = \pi(c_{1k}, c_{2k})$ in market k where c_{ik} is the post R&D marginal cost of firm i in industry k. Defining x_{1k} as its R&D investment, its effective investment is

$$z_{1k} = x_{1k} + \phi x_{2k} + \beta(x_{1k'} + x_{2k'}) \quad \forall\, k \neq k'. \tag{3-26}$$

$\phi x_{2k'}$ and $\beta(x_{1k'} + x_{2k'})$ are intra-industry spillovers within industry k and inter-industry spillovers from industry k' to industry k respectively. As previously,

[35] Though R&D investment is larger in cooperation in the second stage than in non-cooperation, welfare is not necessarily larger in the former. For cooperation induces firms to restrict their output, which results in the higher price. Ziss (1994) shows some conditions for welfare to be larger in the cooperative case.

$A_{1k} = (\partial \pi_{1k} / \partial c_{1k})(dc_{1k} / dz_{1k}) > 0$ and $B_{1k} = (\partial \pi_{1k} / \partial c_{2k})(dc_{2k} / dz_{2k}) \leq 0 \quad \forall k$.[36]

Steurs considered three cases: non-cooperative R&D; intra-industry RJVs where firms in each industry form RJVs; inter-industry RJVs where firm *1* (*2*) in industry *1* form RJV with firm *1* (*2*) in industry *2*. Then he compared the equilibrium level of R&D investment in each case.

As two industries are independent, I can get the net profits and the first order condition for firm *1* in non-cooperative R&D and intra-industry RJVs by substituting (3-26) into (3-5), (3-6), (3-7), and (3-8) accordingly (and adding subscripts *k* to them). As for inter-industry RJVs, firm *1* in industry *k* solves

$$\underset{x_{1k}}{Max}\ T_k = \sum_{k=1}^{2} \Pi_{1k} . \tag{3-27}$$

Therefore, its first order condition is

$$\partial T_k / \partial x_{1k} = A_{1k} + \phi B_{1k} + \beta(A_{1k'} + B_{1k'}) - 1 = 0 \quad \forall k \neq k'. \tag{3-28}$$

Imposing the symmetry conditions on (3-28), and defining the symmetric solution for (3-28) as x^{R2}, I obtain

[36] As two industries are *independent*, $\partial \pi_{ik} / \partial c_{ik'} = \partial \pi_{ik} / \partial c_{i'k'} = 0 \ \forall\ i \neq i',\ k \neq k'$.

$$\partial \Gamma_k / \partial x \big|_{x=x^{R2}} = (1+\beta)A + (\phi+\beta)B - 1 = 0 . \qquad (3\text{-}29)$$

Note that the comparison between x^N and x^{R1} here is the same as in D&J. To compare x^N and x^{R2}, evaluating (3-9) at x^{R2} and substituting (3-29) into (3-9), I get

$$\partial \Pi / \partial x \big|_{x=x^{R2}} = -\beta(A+B) \le 0 . \qquad (3\text{-}30)$$

Result 3-6. $x^N \le x^{R2}$ $\forall \beta, \phi$ *where equality holds only if* $\beta = 0$.

The reason is simple. (3-28) indicates that, when $\beta \neq 0$, firm *1* internalizes two (rent shifting) externalities in inter-industry RJVs, both of which stem from the information leaking from firm *1* in industry *k'*. $\beta A_{1k'}$ is the spillovers externality, which represents the efficiency gain for firm *1* in industry *k'* due to its lower cost and has a positive impact on joint profits. $\beta B_{1k'}$ is the externality of rent shifting from firm *1* to firm *2* in the industry and its impact on joint profits is negative. [37] (3-30) suggests that the effect of $\beta A_{1k'}$ dominates that of $\beta B_{1k'}$ Thus in inter-industry RJVs firm *1* internalizes positive externalities whatever ϕ and β are. However, if $\beta = 0$, R&D investment in one industry has no impact on firms in the other as there is no information leakage across industries. Thus there is basically no difference between non-cooperative R&D and inter-industry RJVs.

[37] $\beta A_{1k'}$ and $\beta B_{1k'}$ are the same as ϕA_1 and B_2 in (3-8) respectively.

Next, evaluating (3-10) at x^{R2} and substituting (3-29) into (3-10), I obtain

$$\partial\Gamma/\partial x\big|_{x=x^{R2}} = (\phi-\beta)A+(1-\beta)B \tag{3-31}$$

The second term in (3-31) is non-positive while the first term is positive iff $\phi > \beta$. Thus, the comparison between x^{R1} and x^{R2} depends on ϕ and β. If $\phi \leq \beta$, then (3-28) is unambiguously negative so that inter-industry RJVs induce more R&D investment than intra-industry RJVs. This is because when ϕ is small, firms internalize negative externalities in intra-industry RJVs but non-negative externalities in inter-industry RJVs whatever ϕ and β are. If $\phi > \beta$ and ϕ is large, firms internalize positive externalities in both RJVs. Steurs showed that, if $\phi > 1/2$, then there is strategic complementarity in R&D investment in both RJVs. If ϕ (β) is sufficiently larger than β (ϕ), the complementarity is stronger in intra (inter) - industry RJVs so that R&D investment is larger in intra (inter) industry RJVs.

Result 3-7. $x^{R1} < x^{R2}$ *if* ϕ *-*β *is either negative or positive but small.* $x^{R1} \geq x^{R2}$ *otherwise.* [38]

Poyago-Theotoky (1995) considers two cases; non-cooperative R&D and a RJV cartel *plus* some competitive fringes. Her aim is to compare the number of firms which join RJVs in equilibrium and the social optimal number. A simplified version of her model is as follows. Suppose that there are three firms. Firm *1*

[38] Steurs (1995) shows that $x^{R1} \geq x^{R2}$ iff $\beta \leq 2\phi$-1 where equality holds if $\beta = 2\phi$ -1 .

conducts R&D on its own while firm *2* and *3* form a RJV cartel. Thus the effective investment of firm *1* is (*2*) plus ϕx_3 in non-cooperative R&D. If a RJV cartel is formed, then the effective investment of firm *1* and firm *2* is written as

$$z_1 = x_1 + \phi(x_2 + x_3) \tag{3-32}$$

$$z_2 = x_2 + x_3 + \phi x_1, \tag{3-33}$$

and the maximization problems for them are

$$\underset{x_1}{Max}\ \Pi_1 = \pi(c_1(z_1), c_2(z_2), c_3(z_3)) - x_1. \tag{3-34}$$

$$\underset{x_2}{Max}\ T = \sum_{i=2}^{3} \Pi_i \tag{3-35}$$

respectively. [39] Then, the first order condition for firm *1* in non-cooperative R&D, and that of firm *1* and firm *2* when a RJV cartel exists are

$$\frac{\partial \Pi_1}{\partial x_1} = \left\{ \frac{\partial \pi_1}{\partial c_1}\frac{dc_1}{\partial z_1} + \left(\frac{\partial \pi_1}{\partial c_2}\frac{dc_2}{\partial z_2} + \frac{\partial \pi_1}{\partial c_3}\frac{dc_3}{\partial z_3} \right)\phi \right\} - 1 = 0 \tag{3-36}$$

$$\frac{\partial \Pi_1}{\partial x_1} = \left\{ \frac{\partial \pi_1}{\partial c_1}\frac{dc_1}{\partial z_1} + \left(\frac{\partial \pi_1}{\partial c_2}\frac{dc_2}{\partial z_2} + \frac{\partial \pi_1}{\partial c_3}\frac{dc_3}{\partial z_3} \right)\phi \right\} - 1 = 0. \tag{3-37}$$

$$\frac{\partial T}{\partial x_2} = \left\{ \frac{\partial \pi_2}{\partial c_2}\frac{dc_2}{\partial z_2} + \frac{\partial \pi_2}{\partial c_3}\frac{dc_3}{\partial z_3} + \frac{\partial \pi_2}{\partial c_1}\frac{dc_1}{\partial z_1}\phi \right\} + \left[\frac{\partial \pi_3}{\partial c_2}\frac{dc_2}{\partial z_2} + \frac{\partial \pi_3}{\partial c_3}\frac{dc_3}{\partial z_3} + \phi\frac{\partial \pi_3}{\partial c_1}\frac{dc_1}{\partial z_1} \right] - 1 = 0. \tag{3-38}$$

[39] What I say about firm *2* applies to firm *3*, too.

Unfortunately, at this level of abstraction, comparing R&D investment in each case is not possible. Marginal revenues in (3-36) are different from those in (3-37) due to the difference in the effective investment. Moreover, if I compare marginal revenues in (3-36) (or (3-37)) with those (3-38), I find that unlike the previous cases, whether RJVs induce more investment is not entirely up to whether firms internalize positive or negative externalities in RJVs. The effect on its own profits of R&D investment by a firm also plays a part in the result. Using a model similar to D&J and some numerical examples, Poyago-Theotoky showed that R&D investment is the largest (smallest) in a RJV cartel (non-cooperative R&D).

Motta (1992) differs from D&J in that firms, which engage in vertical product differentiation, conduct quality improvement R&D. First, firms decide whether to enter an industry. After entry, they conduct R&D, which is followed by Cournot competition. Despite differences in details, his result about the investment is by and large the same as D&J if I fix industry structure. To show that, consider a duopoly case and replace c in (3-5) and (3-6) with q which is quality of products. It is innocuous to assume that

$$A_{1q} = (\partial \pi_1 / \partial q_1)(dq_1 / dz_1) > 0 \quad \text{and} \quad B_{1q} = (\partial \pi_1 / \partial q_2)(dq_2 / dz_2) \leq 0 . \qquad (3\text{-}39)$$

That is, quality improvement of firm 1 (2) increases (decreases or does not affect) profits of firm *1* and the larger effective investment raises quality of products. Replacing (3-39) with A and B in (3-9) and (3-10) yields the similar equation as (3-11). Therefore all arguments there apply here.

Choi (1992) differs from the above papers in two respects. First, in his model, information leakage occurs *after* the R&D stage, not *during* the R&D stage and determines profits of firm *1* in a final good market as follows:

π^D - if both firms succeed in R&D;

0 - if both firms fail in R&D;

$\pi^{SF} = (1-\phi)\pi^M + \phi\pi^D$ - if firm *1 alone* succeeds in R&D;

$\pi^{FS} = \phi\pi^D + (1-\phi)0 = \phi\pi^D$ - if firm *1 alone* fails in R&D;

where π^M denotes monopoly profits. [40]

The second difference is that he considers a stochastic R&D process unlike D&J and many others, who consider a deterministic process. Define as $p_1 = p(x_1)$ the success probability of firm *1* where x_1 is its R&D investment as before.

Thus, in non-cooperative R&D and RJVs firm *1* solves

$$\underset{x_1}{Max} \quad \Pi_1 = p_1[p_2\pi^D + (1-p_2)\pi^{SF}] + (1-p_1)[p_2\pi^{FS} + (1-p_2)0] - x_1. \quad (3\text{-}40)$$

$$\underset{x_1}{Max} \quad T = \sum_{i=1}^{2} \Pi_i \quad (3\text{-}41)$$

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[40] He sets three assumptions about information leakage. First, information leaks *only* from a firm which has succeed in R&D. Second, a successful firm cannot raise its profits even if it receives the information from a successful rival. Third, an unsuccessful firm can enter a final good market only if it gets information from a successful firm and produces a copy, which is no better than the original due to the lack of information, i.e., $\phi \in (0,1]$.

respectively. Thus, the first order conditions for each case are

$$\partial \Pi_1 / \partial x_1 = (p_1)'[\pi^{SF} + \Delta\pi p_2] - 1 = 0. \quad (3\text{-}42)$$

$$\partial \Gamma / \partial x_1 = (p_1)'[\pi^{SF} + \Delta\pi p_2]$$

$$+ p_2[(p_1)'\pi^D + (1-p_1)'\pi^{SF}] + (1-p_2)[(p_1)'\pi^{FS} + (1-p_1)'0] - 1 = 0. \quad (3\text{-}43)$$

where $\Delta\pi = \pi^{SF} + \pi^{FS} - \pi^D$. He shows that iff the spillover rate is large, non-cooperative R&D results in the smaller R&D investment. The reason is as follow. The more firm *1* invests in RJVs, the payoff of firm *2* for its successful R&D , $(1-p_1)\pi^{SF} + p_1\pi^D$, falls while that for its unsuccessful R&D, $p_1\pi^{FS} + (1-p_1)0$, goes up. Iff ϕ is large, the increase is larger than the decrease so that externalities internalized by firm *1*, which are represented in a lower line in (3-43), are positive.

Katz (1986) considers the question on whether RJVs result in larger *effective* investment than non-cooperative R&D in a setting quite different from D&J. His model begins with a membership stage where firms decide whether to join RJVs, which is followed by the stage where firms in RJVs set a rule for R&D investment and R&D output sharing. Then each firm decides the level of its R&D investment to maximize *its own profits,* not joint profit. Finally Cournot competition takes place in a final good market. Here, for simplicity, I assume that sharing rules are pre-determined and either all firms join RJVs or none of them does.

Let s (> 0) denote the share of R&D investment of firm *1* which it must bear for its own R&D. Then the total investment which firm *1* can use for its own R&D is

$$sx_1 + (1-s)x_2 . \tag{3-44}$$

If $s \in (0,1)$, firm *2* shares some of R&D investment of firm *1*. If $s = 1$, firm *1* bears its R&D investment on its own. If $s > 1$, it must bear some investment of firm *2*. Let $0 \le \underline{\phi} \le \overline{\phi} \le 1$ where $\underline{\phi}$ ($\overline{\phi}$) is a spillover rate in non-cooperative R&D (RJVs). [41] Then in non-cooperative R&D and RJVs the effective investment of firm *1* is

$$\underline{z}_1 = x_1 + \underline{\phi} x_2 . \tag{3-45}$$

$$\overline{z}_1 = x_1 + \overline{\phi} x_2 . \tag{3-46}$$

respectively. Given $\overline{\phi}$, $\underline{\phi}$, and s, in non-cooperative R&D and RJVs firm *1* solves

$$\underset{x_1}{Max} \quad \Pi_1 = \pi(c_1(\underline{z}_1), c_2(\underline{z}_2)) - x_1 . \tag{3-47}$$

$$\underset{x_1}{Max} \quad T_1 = \pi(c_1(\overline{z}_1), c_2(\overline{z}_2)) - (sx_1 + (1-s)x_2) . \tag{3-48}$$

respectively. Thus the first order condition for each case is

$$\partial \pi_1 / \partial x_1 = \underline{A}_1 + \underline{\phi} \underline{B}_1 - 1 = 0 \tag{3-49}$$

$$\partial \Pi_1 / \partial x_1 = \overline{A}_1 + \overline{\phi} \overline{B}_1 - s = 0 \tag{3-50}$$

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[41] In Katz, $\underline{\phi}$ is exogenously determined while $\overline{\phi}$ endogenous in RJVs so as to enable firms in RJVs to internalise externalities at the R&D stage.

where $\underline{A}_1(\overline{A}_1)$ and $\underline{B}_1(\overline{B}_1)$ are $A_1\big|_{z=\underline{z}(\bar{z})}$ and $B_1\big|_{z=\underline{z}(\bar{z})}$ respectively. Defining z^N and z^R as the equilibrium effective investment in non-cooperative R&D and RJVs, I get

$$\begin{aligned} \partial\Pi/\partial x\big|_{z=z^R} &= s-\overline{\underline{\phi}\overline{B}}+\underline{\phi}\overline{B}-1 \\ &= (s-1)+(\underline{\phi}-\overline{\underline{\phi}})\overline{B} \end{aligned} \qquad (3\text{-}51)$$

(3-51) shows two key points. First the smaller s, i.e., the more cost (investment) sharing, is more likely to lead to the larger effective investment in RJVs. For, as (3-50) indicates, the cost sharing lowers marginal cost of R&D and, thus, encourages firms to invest in R&D. Second, the larger $\overline{\underline{\phi}}$ leads to the smaller effective investment in RJVs. It would lower $\overline{\underline{\phi}B_1}$ in (3-50), which says that R&D investment by firm *1* hurts itself by making firm *2* more competitive. Thus it is discouraged from investing much in R&D.

4. Critiques

Salant and Shaffer (1998) criticize the symmetric equilibrium assumption in RJVs. The literature deploys this assumption simply because all firms are identical. However, they showed in their numerical example that identical firms in RJVs could be better off by agreeing to invest *asymmetrically.*[42] This would happen if the

[42] If products are substantially differentiated, their result may not hold. For instance, if each of firms is a monopolist due to product differentiation, it is easy to verify that their joint profits are larger with the (non-) equilibrium symmetric investment than with the equilibrium asymmetric one.

spillover rate is small and diminishing returns are not severe. The intuition is as follows. Asymmetric investment is aimed at creating large cost differences between firms so as to create monopoly in a market, suppress competition, and, thus, boost joint profits there. If the spillover rate is small, the large investment by a firm lowers its cost substantially but reduces that of the other firm by a smaller amount, which makes monopolization less costly.[43] Likewise, if diminishing returns are not severe, the large investment does not raise the cost of R&D investment too much. Thus the gain from monopolization can exceed the cost of the large investment.

Moreover, in the asymmetric equilibrium a firm which makes the larger R&D investment in RJVs invests *more* than those in non-cooperative R&D even when it internalizes *negative* externalities.[44] That is, the usual rationale that RJVs lead to more (less) investment than non-cooperative R&D if firms in RJVs internalize positive (negative) externalities does not apply here. To show how that happens, let us suppose that $\phi \approx 0$ for simplicity. Then (3-7) is written as

$$\partial \Pi^{RI} / \partial x_1 = A_1 + \phi B_1 + B_2 + \phi A_2 - 1 \approx A_1 + B_2 - 1 = 0 . \qquad (3\text{-}52)$$

Now suppose (3-3) and the assumption by Katz (1986) that

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[43] If the spillover rate is not sufficiently small, e.g. 0.3 in their example, it is optimal for firms to create asymmetric duopoly, not monopoly. For, there, one firm has to invest in a prohibitively large amount if they want to create a monopoly, which outweighs the gain from monopolisation.

[44] However, Salant and Shaffer showed that the *aggregate* R&D investment would be large in non-cooperative R&D than in asymmetric RJVs.

$$\partial^2 \pi_1 / \partial (c_1)^2 > 0 \geq \partial^2 \pi_1 / \partial (c_2)^2 . \qquad (3\text{-}53)$$

If firm *1* increases its investment so that $x_1 > x_2$ in RJVs, A_1 in (3-52) becomes larger with the increase due to (3-53). As to B_2 in (3-52), $\partial \pi_2 / \partial c_1$ becomes larger but $\partial c_1 / \partial z_1$ smaller in absolute values. If the change in $\partial \pi_2 / \partial c_1$ has a larger impact than that in $\partial c_1 / \partial z_1$, B_2 can be larger in absolute values with the larger x_1 Then an asymmetric equilibrium can exist where firm *1* internalizes negative externalities but $x_1 > x^N > x_2$.

A criticism in Iidaka (1999.a) is about the formulation of RJVs in the literature. The papers on RJVs with spillovers do not incorporate two facts relevant to RJVs, namely, joint use of a successful R&D output by firms in RJVs *and* product differentiation in a final good market.[45] Tao and Wu (1997) mention that once a research output is developed in RJVs, all member firms can usually use it. Moreover, according to Katsoulakos and Ulph (1998), RJVs are often formed by firms in different industries or countries. That is, their products are often different or, due to a geographical factor, differentiated.

Setting up the model which captures the two facts, I showed that research joint ventures could result in the smaller R&D investment than non-cooperative R&D even if the spillover rate is large and in RJVs firms internalize positive externalities.

The result is derived from the following model. Two firms run R&D to develop a

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[45] Combs (1992) and, to some extent, Choi (1992) capture only the former whereas Kamien *et al* (1992) assume only the latter. Most other papers such as D'Aspremont and Jacquemin (1988), Suzumura (1992), Ziss (1994), Vonortas (1994) assume neither.

research prototype. If a firm succeeds in R&D, it gets a payoff in a final good market; π^M if the firm alone enters a market; π^D if the other firm too does so; 0 otherwise. $\pi^M = (>)\pi^D$ if their products are perfectly (imperfectly) differentiated.

Let $p_i = p(z_i)$ denote the probability that firm i succeeds in its project where

$$\text{(i) } p_i \in [0,1)\text{; (ii) } dp_i/dz_i = (p_i)' > 0 > d^2 p_i/d(z_i)^2 = (p_i)''\text{;}$$

$$\text{(iii) } ((p_i)')^2 + p_i(p_i)'' \geq 0 \quad \forall z_i, i.$$

z_i is the effective investment on the project of firm i. Here, unlike in the papers referred earlier, which use the effective investment as a R&D output, I use z_i as *an intermediate R&D input*, as in Beath *et al* (1998).

In RJVs both firms carry out R&D and coordinate their R&D investment so as to maximize their joint profits, as in the literature. If only one firm succeeds in RJVs, the firm lets an unsuccessful firm use its R&D output so that both firms enter a final good market. This formulation of joint use of an output follows Combs (1992).

Thus, in non-cooperative R&D and RJVs firm i solves

$$\underset{x_i}{Max}\ \Pi_i = p_i(1-p_j)\pi^M + p_i p_j \pi^D - x_i \ \forall\ i \neq j. \tag{3-54}$$

$$\underset{x_i}{Max}\ T = [\,p_i + (1-p_i)p_j\,]\pi^D - x_i + [\,p_j + (1-p_j)p_i\,]\pi^D - x_j \quad \forall\ i \neq j \tag{3-55}$$

respectively. Hence the first order conditions in a symmetric equilibrium are

$$\begin{aligned}\partial \Pi_i / \partial x_i &= (p_i)'[(1-p_j)\pi^M + p_j\pi^D] + (p_j)' p_i \phi(\pi^D - \pi^M) - 1 \\ &= (p^N)'[\pi^M + (1+\phi)(\pi^D - \pi^M)p^N] - 1 = 0\end{aligned} \tag{3-56}$$

$$\begin{aligned}\partial \Gamma / \partial x_i &= [(p_i)'(1-p_j) + (p_j)'(1-p_i)\phi]\pi^D + [(p_j)'(1-p_i)\phi + (p_i)'(1-p_j)]\pi^D - 1 \\ &= 2(p^R)'(1-p^R)(1+\phi)\pi^D - 1 = 0\end{aligned} \tag{3-57}$$

Superscripts, N and R, refer to an equilibrium in non-cooperative R&D and RJVs respectively. I assume an interior symmetric Nash equilibrium and that π^D is large so that $3\pi^D > \pi^M$. I can verify that the second order conditions always hold.

Using these assumptions, I got the following result

$x^N \geq x^R$ *iff* $p^* + p^R \geq 0$ *where* $p^* = [\pi^M - 2(1+\phi)\pi^D] / (1+\phi)(3\pi^D - \pi^M)$

and equality holds only if $p^R + p^* = 0$.

For, evaluating (3-55) at x^R and, then, substituting (3-55) into (3-56), I get

$$\begin{aligned}\partial \Pi / \partial x \big|_{x=x^R} &= (p^R)'[(\pi^M - 2(1+\phi)\pi^D) + p^R(1+\phi)(3\pi^D - \pi^M)] \\ &= \underbrace{(p^R)'(1+\phi)(3\pi^D - \pi^M)}_{+}(p^* + p^R)\end{aligned} \tag{3-58}$$

Note that p^* could be either positive or negative. Thus, (3-58) is positive (negative) if $p^* + p^R$ is positive (negative). This implies the result.

There are two factors in determining the result. On the one hand, a term in the second square bracket of (3-57) suggests that in RJVs firms internalize positive externalities. This induces them to expand their investment. On the other hand, joint use of a R&D output discourages them from investing much in R&D for the

following reason. In non-cooperative R&D, a firm gets $(1-p)\pi^M + p\pi^D$ from successful R&D but 0 from failure. However, in RJVs it earns π^D from success but $p\pi^D$ from failure *due to joint use of an R&D output*. Note that given some x, $[(1-p)\pi^M + p\pi^D] - 0 > \pi^D - p\pi^D$. That is, the gap between the payoff of success and that of failure is smaller in RJVs. Choi (1992) showed that the smaller gap between them led firms to invest less. Here, iff $p^* + p^R > (=)0$, the latter factor dominates (cancels out) the former so that $x^N > (=)x^R$.

The result suggests that if products of firms are *substantially* differentiated so that π^D is large, various outcomes are possible. [46] For example, suppose that $\pi^M = \pi^D$. Differentiating p^R and p^* with respect to ϕ, I get

$$\partial p^* / \partial \phi = -\pi^M / [(3\pi^D - \pi^M)(1+\phi)^2] < 0 \quad \forall \phi. \tag{3-59}$$

$$dp^R / d\phi = (p^R)'(dz^R / d\phi) = (p^R)'[(1+\phi)(dx^R / d\phi) + x^R] > 0 \quad \forall \phi.^{47} \tag{3-60}$$

Moreover, p^* = -1/2 (-3/4) if $\phi = 0$ (1). Thus, if $p^R|_{\phi=0} > 1/2$ and $p^R|_{\phi=1} < 3/4$, $p^R + p^* > (<)0$ for a small (large) ϕ and, thus, $x^R < (>)x^N$ for a small (large) ϕ. This is more or less in line with the result of the literature. However, if

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[46] On the contrary, if I assume Cournot competition with *homogenous* goods as in the literature, $\pi^D = 4\pi^M / 9$ and, thus, $p^* = (1-8\phi)/3(1+\phi)$. Note that $p^* = 1/3$ at $\phi = 0$ and $p^* = -7/6$ at $\phi = 1$. Hence, from (3-59) and (3-60), there exists $\phi^* (\in (0,1))$ such that $p^R + p^* > (\leq)0$ if $\phi < (\geq)\phi^*$ so that $x^N > (\geq)x^R$ if $\phi < (\geq)\phi^*$. This result is by and large the same as that in the literature.

[47] Applying the implicit function theorem to (3-57) shows that a term in square brackets in (3-60) is positive.

$p^R\big|_{\phi=0} < 1/2$ and $p^R\big|_{\phi=1} > 3/4$, then $x^R > (<) x^N$ for a small (large) ϕ, which is quite opposite to the standard result. Moreover, if p^R is very low (high) for all ϕ so that $p^R + p^* < (>) 0 \ \forall \phi$, RJVs (non-cooperative R&D) lead to the larger R&D investment whatever the spillover rate is. Which of the results emerges depends on the exact form of the probability function and parameters.

The contrast between the result of the standard models and mine is obvious. The former says that if the spillover rate is large, RJVs induce *more* R&D investment than non-cooperative R&D as firms in RJVs internalize positive externalities. This holds even if product differentiation is introduced as in Kamien et al (1992). On the contrary, my result indicates that if the rate is large *and* products are substantially differentiated, RJVs can result in *less* R&D investment even if firms internalize positive externalities.

Katsoulacos and Ulph (1998) object to spillovers being *exogenous*. [48] In non-cooperative environments, a firm would keep its research information to secret in order not to let its competitors benefit from the information. [49] On the contrary, in RJVs firms may be willing to share their research information to benefit of other member firms. Katsoulacos and Ulph analyzed to what extent firms want to reveal information on their research output in non-cooperative R&D and RJVs.

In addition to endogenous spillovers, they also mentioned that in RJVs running two labs, which is assumed in the literature, could be Pareto inferior to running just

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[48] Katz (1986) and De Fraja (1992) too analyse R&D where the spillover rate is chosen by firms.

[49] In reality, firms may control the flow of their research information. For instance, Moseley (1989) says that as a result of close daily supervision and control, the project manager of a firm can maintain commercial confidentiality by restricting some research information on a need-to-know basis.

one. [50] There are two possible reasons for this. First, if two labs run the same or similar projects, then there will be much wasteful duplication in their research. In this case, running only one lab eliminates that and, thus, saves some *aggregate* cost for R&D to some extent. The second is for an anti-competitive reason. If both labs succeed in R&D, a final good market is certainly duopoly. However, if only one lab runs, then they can create (the situation which is almost like) monopoly there. As shown in Salant and Shaffer (1998), this can boost joint profits of firms in RJVs.

5. Relation with the present work.

My analysis of R&D organization in the biotechnology industry builds much on the framework used in the models sketched above, as they share two key features that fit the biotechnology industry well.

First, the literature uses a non-tournament framework which captures two important aspects of the industry; (i) it assumes many research paths available to firms. In the biotechnology industry, firms can develop a new product by using various combinations of host, carrier vectors, and chemical compounds; (ii) a non-tournament model assumes that the patent protection awarded to an first innovator is weak so that it cannot prevent its rivals from entering a market with their own research output. According to the Association of the British Pharmaceutical Industry (1985), effective patent protection lasted only 5 years in 1980, and this figure had been on the decline. Thus, firms develop their own product after the first innovator can enter a market only with a little delay. Also, Sutton (1998) shows

[50] Here, if firms decide to run only one lab, they simply shut down the other, instead of pooling their

that R&D in the pharmaceutical industry is not a winner-take-all tournament.

Second, the above literature considers externalization/internalization of externalities. I assume *intra-unit* externalities, i.e., externalities *within* a R&D unit, which are internalized (externalized) in In-house R&D (contractual R&D).

However, the models developed in this work differ from the literature in two aspects in order to incorporate some features specific to the biotechnology industry.

First, unlike the literature which considers single project R&D by single product firms, I consider multi project R&D by multi-product firms. [51] According to OTA (1984), in the biotechnology industry firms are usually multi-product and run *several* projects aimed at different innovations. In biotechnology many techniques have a wide range of industrial applications, as shown in Chapter 2. Thus, *project cross fertilization* is likely to arise in their R&D activities.[52] I assume that a firm can take full advantage of the cross fertilization only if it runs all projects internally.

Secondly, in the literature referred above the size of a research team of a R&D unit is invariant whether RJVs or non-cooperative R&D. In this thesis, the size of a team (per project) is endogenous to R&D organization, thereby enabling me to analyze the size effect. Delegating a project to a lab enables a firm to put its researchers on the smaller number of internal projects. This subsequently enlarges the size of each project team and enhances its productivity or information

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complementary R&D resources into the single lab and sharing their research know-how.

[51] Sah and Stiglitz (1989) examine multi project R&D where each firm runs parallel projects, all of which are aimed at the same innovation.

[52] Fn. 20 mentions the example of Roche and Glaxo.

assimilation ability. [53] In my models, the size of each product team affects the productivity of a unit, as the absorptive ability in Cohen and Levinthal (1989) does. While they assume that the ability is determined with R&D investment, I assume for simplicity that the ability resulting from the size is independent of investment.

In the next three chapters, I will set up the model which incorporate all these points and analyze how the organizational differences affect market outcomes.

[53] Gittins (1997) argues for contractual R&D from this viewpoint.

Chapter 4. An Analysis of contractual and in-house R&D

1. Introduction

This chapter examines profitability and social welfare under In-house and contractual R&D. Here, my analysis is confined in two symmetric cases: the one where both firms use in-house R&D, which I call the Integrated (I) regime, and the other where both use contractual R&D, which I call the Separated (S) regime. Using the results from the analysis, I will also advance a conjecture on the impact of the expansion of contractual R&D on profitability and welfare in the biotechnology industry. I will do so by constructing the growth as a switch from the I regime to the S regime, applying the facts of the industry to the results in the I regime and the S regime, and examining in which regime profits and welfare are larger.

The organization of the chapter is as follows. Section 2 presents the model. Section 3 characterizes an equilibrium in R&D competition in two symmetric cases and show two preliminary results. Section 4 and 5 examine profitability and social welfare under them respectively. Section 6 concludes.

2. The model

Two multiproduct firms (indexed by $i = 1, 2$) conduct R&D which is aimed at two *independent* markets. [54] If a firm uses Integrated R&D, it runs two *different*

[54] This would be the case quite frequently in biotechnology where R&D is aimed at applications in

projects (indexed by $k = a, b$) in parallel. [55] If it chooses Separated R&D, it runs project a but delegates project b to profit maximizing lab j ($= i$) where $j = 1,2$. All R&D units are endowed with the same menu of projects and productivity. If project k is successful, a firm gets a research output either by internal transfer or from its lab and reaps the following payoffs in market k: π^D if its rival too operates there; π^M if the firm alone does so; 0 otherwise.

3. R&D competition

Let $p_{uk}(z_{uk})$ denote the probability that unit u succeeds in project k where z_{uk} is effective investment. I assume that

$$\text{(i) } p_{uk} \in [0,1)\text{; (ii) } dp_{uk}/dz_{uk} = (p_{uk})' > 0 > d^2 p_{uk}/d(z_{uk})^2 = (p_{uk})''$$

$$\text{(iii) } ((p_{uk})')^2 + p_{uk}((p_{uk})'') \geq 0 \; \forall \, z_{uk} \geq 0 \text{ and } (u, k) = (i, k), (j, b).$$

(i) says that success probability is non-negative and strictly smaller than 1. (ii) indicates that the probability function is strictly concave in effective investment. (iii) ensures that the second order condition (SOC) is always satisfied.

When both firms use Integrated R&D, effective investment of project k by firm i is

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quite separate market (e.g. pharmaceutical and speciality chemical).

[55] Throughout the thesis, the number of projects for a firm is exogenously fixed at 2 for simplicity. Appendix 4-B shows what will happen if firms under Integrated R&D can choose not only the level of R&D investment per project but also *the number of projects* in a somehow different circumstance.

$$z_{ik} = \theta[x_{ik} + \gamma x_{ik'} + \phi(x_{i'k} + \gamma x_{i'k'})] \quad \forall i \neq i', k \neq k'. \tag{4-1}$$

x_{ik} is the investment made in project k. $\gamma x_{ik'}$ is the internal *project* spillovers resulting from cross fertilization between researchers of project k and those of project $k'(\neq k)$. $\gamma(\in[0,1])$ is the applicability rate of information generated in project k' to project k. $\phi(x_{i'k} + \gamma x_{i'k'})$ is the inter *unit* spillovers where $i' \neq i$ and $\phi \in [0,1]$. [56] $\theta(\in[1/2,1])$ is the (negative) size effect. This would lower the productivity or the assimilative ability of a firm *because* it has to spread its R&D personnel to two project team, which reduces the size of each team and, thus, adversely affects its productivity. [57]

If both firms use Separated R&D, the effective investment on project a by firm i consists of the investment on project a and the spillovers from other units:

$$z_{ia} = x_{ia} + \phi[x_{i'a} + \gamma(x_{jb} + x_{j'b})] \quad \forall (i,j) = (1,1), (2,2) \text{ where } i \neq i', j \neq j'. \tag{4-2}$$

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[56] Here, the inclusion of $\phi = \gamma = 1$ is solely for completeness.

[57] The assumption that $\theta \in [1/2.1]$ stems from the finding by Henderson and Cockburn (1996) that *at the project level* there are decreasing returns to investment in R&D for pharmaceuticals. It is innocuous to presume from this that there are also decreasing returns to non-monetary inputs such as time and effort of each project team. Note that in Separated R&D a firm effectively uses the non-monetary input *per project* twice as much as in Integrated R&D. Then, given R&D investment in a project and excluding all spillovers, the R&D output, i.e. the effective investment, in Separated R&D ($z = x$) should be less than double of that in Integrated R&D ($z = \theta x$), i.e., $1/2 < \theta < 1$. I include 1/2 and 1 solely for convenience.

Swapping i with j and a with b, I can define the effective investment of lab j.[58] Here, as the size of a project team is effectively twice as large as that in Integrated R&D, the size effect vanishes. Moreover, the productivity of the team goes up. I will call the resultant high productivity the *specialization effect*.

In the first case, which I call the I regime, firm i solves

$$\underset{x_{ia},x_{ib}}{Max}\ \Pi_i = [p_{ia}(1-p_{i'a})+p_{ib}(1-p_{i'b})]\pi^M + (p_{ia}p_{i'a}+p_{ib}p_{i'b})\pi^D - x_{ia} - x_{ib}\ \forall\ i \neq i'. \quad (4\text{-}3)$$

In the second case, which I call the S regime, firm i and lab j solve

$$\underset{x_{ia}}{Max}\ \Pi_i = p_{ia}(1-p_{i'a})\pi^M + p_{ia}p_{i'a}\pi^D - x_{ia} + F \quad \forall\ i \neq i'. \quad (4\text{-}4)$$

$$\underset{x_{jb}}{Max}\ \Pi_j = p_{jb}(1-p_{j'b})\pi^M + p_{jb}p_{j'b}\pi^D - x_{jb} - F \quad \forall\ j \neq j'. \quad (4\text{-}5)$$

F is firm i' s profits from project b (*net* of the research fee paid to its partner lab). For simplicity, it is assumed to be *exogenous* and to solve $\Pi_j = 0$ in equilibrium.

I confine the analysis to the I and the S regime cases for simplicity. Hence

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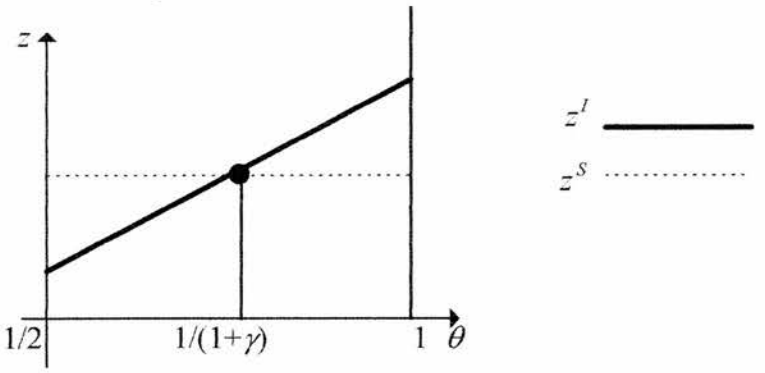
[58] Most papers mentioned in Chapter 3 do not distinguish the degree of usefulness of information, γ, from that of information leakage across units, ϕ. (As far as I know, only Katsoulacos and Ulph (1998) make the similar distinction). While it does not matter in the papers (possibly except for Steurs (1995)), the distinction is important here as ϕ and γ have different implications for some of my main results.

Figure 4-1



$$\partial \Pi^I / \partial x = \theta(1+\gamma)(p^I)' A^I - 1 = 0 \tag{4-6}$$

$$\partial \Pi^S / \partial x = (p^S)' A^S - 1 = 0 \tag{4-7}$$

where $A^r = \pi^M + \Delta\pi(1+\phi)p^r$, $\Delta\pi = \pi^D - \pi^M < 0$, and $r = I, S$.

The superscripts I and S refer to an equilibrium in the I and the S regimes respectively. A symmetric *interior* Nash equilibrium is assumed so that $A^r > 0$. The second order conditions always hold.

Using the FOCs, I obtain two useful preliminary results. The first result is

Lemma 4-1. $z^I \geq z^S$ *iff* $\theta \geq 1/(1+\gamma)$ *where equality holds at* $\theta = 1/(1+\gamma)$.

Figure 4-1 illustrates this result. It says that, when θ is small, effective investment is larger in the S regime than in the I regime, and *vice versa*. When θ is small, a R&D unit has a low assimilative ability in the I regime due to the size effect. This prevents it from accumulating efficiently the information of projects. Putting all researchers to one project with delegation raises its assimilative ability and solves this problem.

Figure 4-2(a)

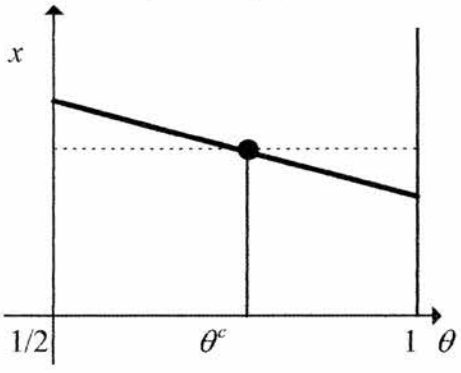
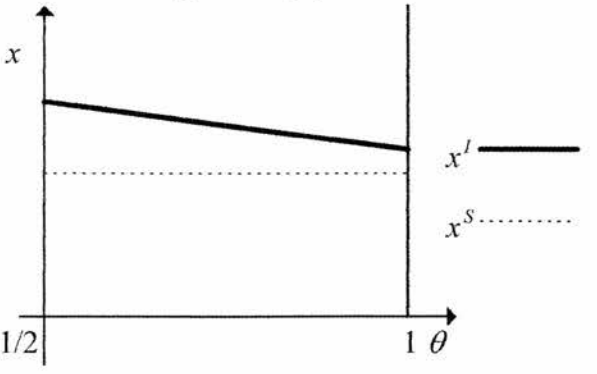


Figure 4-2(b)



When θ is large, a unit in the I regime can assimilate the information relatively efficiently due to the not-so-severe size effect. Together with the information via cross fertilization, this unit can accumulate much information for each project.

The second preliminary result is

Lemma 4-2. Suppose that $(p^I)' + (p^I)''z^I < 0 \quad \forall\theta$. *If* $\phi \le \phi^c (\in [0,1))$, $\exists\, \theta^c (\in (0,1])$ *s.t.* $x^I \ge x^S$ *iff* $\theta \le \theta^c$ *where equality holds at* $\theta = \theta^c$. *Otherwise,* $x^I > x^S \quad \forall\theta$.

Figure 4-2 (a) and 4-2(b) illustrates the first and the second result respectively. I examine only the first case as the second one is not so relevant to my later results. It says that the investment is larger in the *I* regime than in the *S* regime if the size effect is severe, i.e. a small θ, and *vice versa*. The key of this result is the fact that γ is the rate of *negative* externalities, [59] and in the *I* regime a unit internalizes them while it does not in the *S* regime. Interestingly, when θ is small the investment is

[59] For this, see (A.4-9) and (A.4-11) in Appendix 4-A.

larger in the *I* regime though a unit internalizes *negative* externalities. It is because θ *weakens* the effect of externalities, which boosts the investment in the *I* regime.

4. Comparison of profits

Using the preliminary results, this section compares profitability in the *I* and the *S* regimes. Importantly, the result differs according to p^I. If p^I is relatively small, the organization which induces the *larger* effective investment yields the larger profits. However, if p^I is relatively large, the one which induces the *smaller* effective investment generates the larger profits (in most circumstances).

The point of the result lies in the behavior of gross profits. My comparison between contractual R&D and in-house R&D is somehow analogous to that between non-cooperative R&D and inter-industry RJVs in Steurs (1995). Thus, comparing between my result and his will highlight the point. In his model (and most others dealing with the deterministic R&D process in the literature of RJVs) gross profits are *always increasing* in effective investment. Hence, from Result 3-6 in Chapter 3, gross profits are always larger in inter-industry RJVs (unless $\phi = \beta = 0$ in (3-26) in Chapter 3), which tends to lead to the larger net profits there.[60] On the contrary, in my model (4-8) and the assumption that $(p^r)' > 0$ imply that gross profits are either decreasing, or increasing, or both in the effective investment.

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[60] He showed that inter industry RJVs could result in the *smaller* net profits if ϕ and β are small. For, when they are small, the difference between the effective investment in RJVs and that in non-cooperative R&D is small. However, RJVs induce too much investment relative to non-cooperative R&D due to internalisation of positive externalities. Thus, overall, net profits are smaller in RJVs.

Thus, if they are increasing (decreasing) in effective investment, the organization that produces the larger (smaller) effective investment yields the larger gross profits. They subsequently lead to the larger net profits here in most situations.

Together with lemma 4-2, this result implies that in some circumstances the *less* competitive R&D and the *higher* success probability result in the larger profits. On the other hand, intriguingly in other cases the *more* competitive R&D and the *lower* probability result in the larger profits.

Using the results on profitability, I will advance a conjecture on whether the expansion of contractual R&D will lead to higher profitability in the biotechnology industry. I show that it depends on the degree of competition of downstream markets and whether R&D is aimed at novel product or standard products.

Below, I will present these results in detail.

Proposition 4-1. *If* $(p^I)'+(p^I)''z^I<0$ *and* $p^I \in (0,-\pi^M/2\Delta\pi]$ $\forall\theta$, *and* θ^c *exists,* $\exists\ \theta_1^{cII}(\in[1/(1+\gamma),\theta^c])$ *s.t.* $\Pi^I \le \Pi^S$ *iff* $\theta \le \theta_1^{cII}$ *where equality holds at* $\theta=\theta_1^{cII}$

Proposition 4-2. *If* $(p^I)'+(p^I)''z^I<0$ *and* $p^I \in (-\pi^M/2\Delta\pi, -\pi^M/(1+\phi)\Delta\pi)$ $\forall\theta$,*and* ϕ *is large, then* $\exists\ \theta_2^{cII}(\in(0,1/(1+\gamma))]$ *s.t.* $\Pi^I \ge \Pi^S$ *if* $\theta \le \theta_2^{cII}$ *where equality holds at* $\theta=\theta_2^{cII}$.

The first and the second result are illustrated in Figure 4-3(a) and 4-3(b) respectively. Proposition 4-1 (4-2) considers the case where the success probability

Figure 4-3(a)

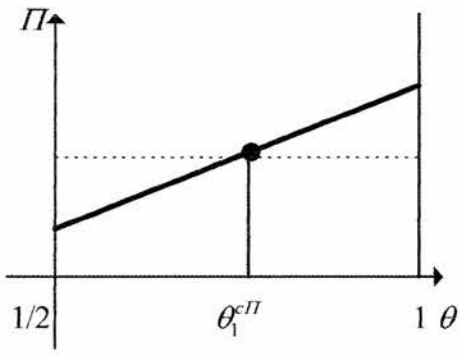
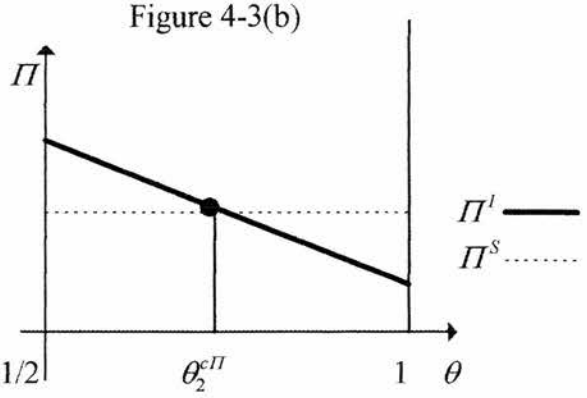


Figure 4-3(b)



is relatively *low* (*high*). [61] In the former, the severe (not so severe) size effect would result in the *larger* profits in the S (I) regime while this is reversed in the latter. Propositions 4-1 and 4-2 are driven mainly by the behavior of gross profits. Note that

$$d[(p^r)^2\pi^D + p^r(1-p^r)\pi^M]/dp^r = \pi^M + 2\Delta\pi p^r. \tag{4-8}$$

(4-8) says that gross profits are uniquely maximized at $p^r = -\pi^M / 2\Delta\pi$ and increasing in p^r if and only if $p^r < -\pi^M / 2\Delta\pi$. If $p^I \le -\pi^M / 2\Delta\pi \ \forall\theta$, lemma 4-1 implies that $p^I < p^S < -\pi^M / 2\Delta\pi$ for a small θ and $p^S < p^I \le -\pi^M / 2\Delta\pi$ for a large θ. [62] Thus, if θ is small, the probability is lower than $-\pi^M / 2\Delta\pi$ in the I

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[61] I can verify that a larger γ *lowers* $\theta_1^{c\Pi}$ while a larger ϕ *raises* it. Thus, the former (latter) change widens a range of θ where Integrated (Separated) R&D is more profitable. As for $\theta_2^{c\Pi}$, a larger γ lowers it whereas the effects of a larger ϕ are ambiguous.

[62] $z^S < z^I$ for a large θ from lemma 4-1. Then if $p^I \le -\pi^M / 2\Delta\pi$, $p^S < p^I \le -\pi^M / 2\Delta\pi$ for a large θ as $(p^r)' > 0$. When θ is small, $p^I < p^S$ as $z^I < z^S$. This, the above inequalities, and the fact that $dz^S / d\theta = 0 \ \forall\theta$ yield $p^I < p^S < -\pi^M / 2\Delta\pi$ for a small θ.

regime, which yields small gross profits according to (4-8). This and lemma 4-2 suggest that a small θ unambiguously leads to the larger profits in the S regime.

If $-\pi^M / 2\Delta\pi < p^I \ \forall\theta$, fn. 62 suggests that $-\pi^M / 2\Delta\pi < p^I < p^S$ for a small θ and $-\pi^M / 2\Delta\pi < p^S < p^I$ for a large θ. Thus, the probability is in excess of $-\pi^M / 2\Delta\pi$ in the S regime when θ is small, which results in such small gross profits according to (4-8). Thus the net profits are larger in the I regime for a small θ even though aggregate investment is smaller in the S regime.

The intuition of these results is simple. When the probability is relatively low, the organization which produces the higher probability is more profitable. For it makes *any given firm* more likely to reap positive payoff in a product market. However, if the probability is relatively high, such an organization turns out to be less profitable. For *its rival firm* (*and its lab*) has a good chance of success in R&D so that any given firm is quite likely to face competition in the market if it operates there.

The implications of two propositions are best appreciated by examining the effect of organization on investment and success probability. If the success probability is low, the organization which induces units to behave *less competitively* and results in the *higher* probability yields larger profits. On the contrary, in the high probability case the one which makes units to act *more competitively* and leads to the *lower* probability yields larger profits.

Alternatively, note that, when θ is small, Separated R&D is efficient relative to the other in that it produces the higher probability from the smaller investment. Combined with two propositions, this implies that, in proposition 4-1 (4-2), the *more (less) efficient* organization leads to the higher profitability.

I am now in a position to use the propositions to advance a conjecture on whether the expansion of contractual R&D in the biotechnology industry will result in the higher profitability. Note that the I can be viewed as the case where there is no expansion (so that no firms use contractual R&D) while the S regime as the one where there is the expansion (so that all firms use contractual R&D). Thus, I will compare two regimes to see the effect of the expansion on profitability.

Using some reasonable estimates of key variables in my model taken from the empirical literature on the biotechnology industry, I will determine which of the propositions applies to the industry.

Struck (1994) argues that the average success probability of development of a prototype of (relatively) *standard* biological products would be 0.53. [63] However, if R&D is for truly *novel* products, then the probability will be very low - about 0.0125.[64] I reason that $\theta(1+\gamma) < 1$ is likely to apply in the biotechnology industry. Halliday *et al* (1997) showed that many firms used contractual R&D due to lack of capacities. This may mean that a R&D unit of a large firm is not large enough to

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[63] Two caveats are in order. First, he mentions the possibility of overestimation. Second, he may have derived this result from projects run under not only in-house R&D but also contractual R&D. Below, I assume, for the sake of argument, that his result reflects p^I as a first approximation.

[64] According to The Economist (1998), the top ten big drug companies launched an average of only 0.45 truly new drugs between 1990 and 1994 a year each. Halliday *et al* (1997) show that in 1992 each of top ten drug firms tried 36 new chemical entities on average as a candidate for a new drug. Even though two sets of top ten companies may not coincide, I assume they do, i.e. as a first approximation. Let us assume, solely for argument, that each unit runs 36 projects and 0.45 molecules are developed from one of them. Then, taking into account uncertainties in R&D, the probability that each project will yield a new compound successfully is lower than 0.0125.

undertake all projects in-house efficiently or, equivalently, that each of its project teams is not large enough to run its project efficiently. Then, it is not unreasonable to infer that θ is small so that $\theta(1+\gamma) < 1$ is more likely than otherwise. However, due to the highly interdisciplinary nature of biotechnology, γ is unlikely to be small. That is, $\theta(1+\gamma)$ is not too close to 1. I have no information about the profitability of the final good market. Thus I will consider separately two polar cases; the less competitive Cournot duopoly and the competitive Bertrand duopoly yielding zero profits. Let us assume, for simplicity, that firms have the constant marginal cost and face a linear demand function. Thus, in the Cournot case, $\pi^D = 4\pi^M / 9$, which yields $-\pi^M / 2\Delta\pi = 0.9$ whereas in the Bertrand case $\pi^D = 0$, i.e. $-\pi^M / 2\Delta\pi = 0.5$. Note that the *I* regime can be viewed as the case where there is no expansion of contractual R&D while the *S* regime as the one where there is (so that firms use contractual R&D). Thus, to derive the conjecture, I will use this information to identify the likely situation in the biotechnology industry, and, then, compare the outcomes of both regimes in the situation. [65]

First, let us consider the Cournot case. Here, the expansion of contractual R&D would result in higher profitability. In fact, as $0.0125 < 0.9$ and $0.53 < 0.9$, proposition 4-1 applies. The point is that a firm can earn large profits in an uncompetitive market from successful R&D *whether or not* its rival firm enters the

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[65] In the conjectures, I make some counterfactual assumptions to simplify the arguments. Some of them will not matter to the main results and conjectures while others will. For instance, the relaxation of the assumptions of the same menu of research projects across firms or of the symmetric research productivity between a firm and a lab will not affect the result and, subsequently, my conjecture so much. However, if $p^{Ia} < -\pi^M / 2\Delta\pi < p^{Ib}$ due to, say, the different nature of two projects, this may or may alter our main results and our conjectures, depending on circumstances.

markets. Then, what is important for a firm is to achieve the high success probability anyway, which is more likely under Separated R&D due to the specialization effect.

In the Bertrand case, the expansion leads to higher profitability if R&D is intended for novel products. As $0.0125 < 0.5$, proposition 4-1 is still likely to apply. On the one hand, Separated R&D results in the higher chance for a firm to get the payoff, π^{M}, than under Integrated R&D. On the other hand, this makes it more likely for its rival firm to enter the market, which will lead to fierce competition if both firms operate there. Here, the former effect outweighs the latter so that firms are better off under Separated R&D.

If R&D is for standard products, the expansion could lead to lower profitability. As $0.53 > 0.5$, proposition 4-2 is likely to apply here. [66] As θ is not too close to $1/(1+\gamma)$, the latter effect in the above dominates the former.

If my model is extended to N (>2) firms, some of the above results would be altered. For instance, take the Cournot case with standard products. As N rises, the critical value $-\pi^{M}/2\Delta\pi$ is likely to be replaced with a smaller one.[67] Then, for

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[66] One of the *sufficient* conditions for proposition 4-2 was a large ϕ, but, in reality ϕ may not be large in (non-cooperative) in-house R&D and contractual R&D. In fact, Katsoulacos and Ulph (1998) showed that if firms compete in the same industry, ϕ should be small. The reason why, nevertheless, I use the result here rests a result in Chapter 6 which implies that $\theta_2^{eII} = 1/(1+\gamma)$ if $\phi = \pi^{D} = 0$ and $p^{I} > 1/2 \ \forall\theta$. (The result shows that $\theta_2^{eII} = (1-\theta)/\theta$ if $\phi = \pi^{D} = 0$ and $p^{I} > 1/2 \ \forall\gamma$. It is easy to verify that this implies that $\theta_2^{eII} = 1/(1+\gamma)$ if $p^{I} > 1/2 \ \forall\theta$). If I presume that this result applies here, which is innocuous due to the qualitative similarity between the model here and the one there, I can show that proposition 4-2 holds for all ϕ.

[67] For instance, let $\pi^{T}(=\pi^{M}/4)$ denote a payoff in market k in a triopoly case. Then reformulating

some $N(>2)$ the critical value will be smaller than 0.53 so that propositions 4-2 is more likely to apply to the case. This means that the expansion would result in the lower profitability in that case if N is large and θ is not so close to $1/(1+\gamma)$.

5. Welfare comparisons

This section compares social welfare under Integrated R&D and Separated R&D. Here, the regime where units invest *less* but generates the *larger* effective investment results in the larger welfare. This is somewhat in contrast with Steurs (1995). He showed that inter-industry RJVs, which induces the *larger* investment and, thus, yields the *larger* effective investment, would produce the larger welfare than non-cooperative R&D.

In Steurs (1995), the point is that the larger welfare stems solely from the larger R&D investment, which results from internalization of positive externalities. On the other hand, in mine the larger welfare in one regime results not from the larger R&D investment but largely from the efficient information assimilation process of units.

The result enables me to advance a conjecture on whether the expansion of contractual R&D will result in larger welfare . It shows that it will no matter what the competitiveness of downstream markets and the nature of R&D are. However, perversely, increase in welfare will come with the exacerbated market failure.

The rest of the section shows these results in detail.

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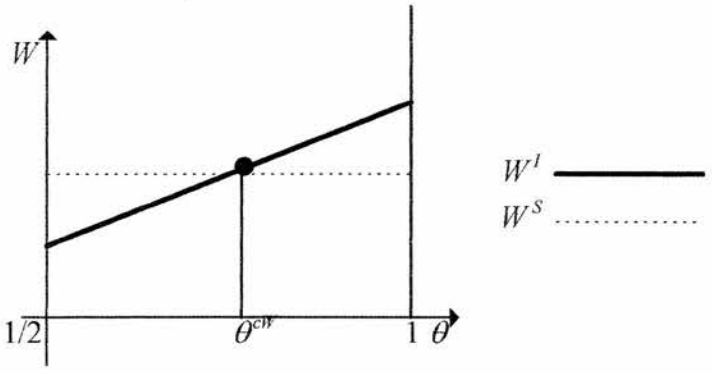
the objective functions accordingly and using the method in the proof of the propositions, it can be shown that 0.9 would be probably replaced with 0.667 or 0.6201.

Figure 4-4



Let ω^M and ω^D denote social welfare in a product market under monopoly and duopoly respectively. Then, the net expected social welfare in regime r is defined as

$$W^r = 2\left[\omega^D\left(p^r\right)^2 + 2\omega^M p^r\left(1-p^r\right) - 2x^r\right] \qquad (4\text{-}9).$$

Invoking (4-9), lemma 4-1, and 4-2, I now establish my second main result.

Proposition 4-3. If $(p^I)' + (p^I)''z^I < 0 \ \forall\theta$ *and* θ^c *exists,*

$\exists\ \theta^{cW}\ (\in [1/(1+\gamma), \theta^c])$ *s.t.* $W^I \geq W^S$ *if* $\theta \geq \theta^{cW}$ *where equality holds at* $\theta = \theta^{cW}$.

Figure 4-4 depicts the result. It says that a severe size effect results in the larger welfare in the S regime than in the I regime, and *vice versa.*[68] The rationale of this result is simple. A small θ leads to the smaller investment in the S regime due to the weakened negative externality effect of γ in the I regime. Moreover, note that

[68] A larger $\gamma(\phi)$ *lowers* (*raises*) θ^{cW}, which means that, with the change, Separated (Integrated) R&D is socially preferable in a wider range of θ.

$$dW^r/dp^r = 4[\omega^M(1-2p^r)+\omega^D p^r] = 4[\omega^M(1-p^r)+(\omega^D-\omega^M)p^r] > 0 \quad (\omega^D > \omega^M). \quad (4\text{-}10)$$

(4-10) and lemma 4-2 imply that gross welfare is larger in the *S* regime for a small θ. For the higher probability there means the higher chance of competition in a market and, sometimes, of introduction of a new product (in monopoly) there as well.

The result suggests that the organization that induces units to act *less* competitively in R&D could yield the *greater* welfare. This contradicts the conventional argument that, *for a given industry structure*, the more competitive market leads to the more efficient resource allocation. The reason for this is that *the R&D organization of firms* could matter more to social welfare than *how competitive R&D is*. Fierce R&D competition induces the large input from each unit. However, the unit would fail to generate the correspondingly large output if, due to its organization, it has a low assimilative ability. Here, this sort of inefficiency arises in Integrated (Separated) R&D when θ and/or γ are small (large). Such organizational inefficiency leads to social inefficiency.

The result shows that the expansion of contractual R&D in the biotechnology industry would lead to larger social welfare whatever the nature of R&D and of downstream market competition is. However, at the same time, the expansion would make worse market failure caused by externalities .[69] This has a perverse

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[69] Defining x^{I^*} and x^{S^*} as the maximiser of (4-9) in the *I* and the *S* regime respectively, I can figure out that $x^{I^*} < x^{S^*}$ if $\theta(1+\gamma) < 1$. Thus, using lemma 4-2 and the fact that externalities yield a socially inefficient outcome, I get $0 < x^{I^*} - x^I < x^{S^*} - x^S$ if $\theta(1+\gamma) < 1$. That is, the expansion widens the divergence between the socially optimal level of investment and the equilibrium level.

policy implication for the government which seeks a socially first best outcome with R&D subsidy as in Leahy and Neary (1997). For, though the expansion results in the *larger* welfare, such a government has to provide *more* R&D subsidy when there is the expansion than when there is not.

6. Conclusion

This chapter examined profitability and social welfare under in-house R&D and contractual R&D in the duopolistic R&D competition. Whereas welfare differences can be attributed entirely to organizational differences, profit comparison depends not only on that but also on the success probability of a project. Using the results, I conjectured the impact on market outcomes of the expansion of contractual R&D in the biotechnology industry. The expansion is likely to result in the larger welfare there. Whether it will lead to the higher profitability would depend on the degree of competitiveness of downstream markets and whether R&D is aimed for standard products or novel products.

All of my discussions are based on the results of two symmetric cases. They can certainly tell me what will happen if all firms switch to contractual R&D. However, it remains unclear how profits and welfare will be affected if only some firms use contractual R&D and others stick with their in-house R&D. The extension of the current model so as to incorporate the asymmetric case and obtain more thorough information about the impact of the expansion is what I will do in the next chapter.

Appendix 4-A

Proof of lemma 4-1. Evaluating (4-6) at $z = z^S$ and substituting (4-7) in (4-6), I get

$$\left.\frac{\partial \Pi^I}{\partial x}\right|_{z=z^S} = (p^S)' A^S[\theta(1+\gamma)-1] \Rightarrow z^I \gtrless z^S \text{ if } \theta \gtrless \frac{1}{1+\gamma} \because (p^S)' A^S > 0. \quad \text{Q.E.D.}$$

Proof of lemma 4-2. In the proof, I examine three cases: (i) $\gamma = 0$: (ii) $\gamma \neq 0 = \phi$: (iii) $\gamma \neq 0 \neq \phi$. At first, suppose that $(p^I)' + z^I(p^I)'' < 0 \ \forall \theta$. Then applying the implicit function theorem to (4-6), I get

$$\frac{dx^I}{d\theta} = -\frac{A^I[(p^I)' + z^I(p^I)''] + \Delta\pi(1+\phi)((p^I)')^2 z^I}{\theta^2(1+\gamma)(1+\phi)[A^I(p^I)'' + \Delta\pi(1+\phi)((p^I)')^2]} < 0 \ \forall \theta. \qquad \text{(A.4-1)}$$

Now suppose that $\gamma = 0$. Lemma 4-1 implies that at $\theta = 1$

$$\theta = 1 = 1/(1+\gamma) \Rightarrow z^I = (1+\phi)x^I = z^S = (1+\phi)x^S \Rightarrow x^I = x^S. \qquad \text{(A.4-2)}$$

Hence, from (A.4-1), I get $x^I \geq x^S \ \forall \theta$ where equality holds only if $\theta = 1$.

Next let us consider the case where $\gamma \neq 0 = \phi$. Substituting $\phi = 0$ and $\theta = 1/(1+\gamma)$ into z^I and z^S, I get $z^I = x^I = x^S = z^S$. This and (A.4-1) suggest that there exists a value of θ, θ^c, such that

$$x^I \gtrless x^S \text{ as } \theta \lessgtr \theta^c (= 1/(1+\gamma)) \qquad \text{(A.4-3).}$$

Finally, let us suppose that $\gamma \neq 0 \neq \phi$. Note that (A.4-3) and the obvious continuity of x^r in ϕ ensure that θ^c exists for some positive ϕ.

Lemma 4-3. θ^c *is strictly increasing in* ϕ.

Proof. Define $\theta^\alpha = [1+\phi(1+2\gamma)]/(1+\phi)(1+\gamma)$. If $\gamma \neq 0 \neq \phi$, $1/(1+\gamma) < \theta^\alpha$. Then

$$z^I = \theta(1+\gamma)(1+\phi)x^I > z^S = [1+\phi(1+2\gamma)]x^S \Rightarrow x^I > x^S \text{ at } \theta = \theta^\alpha .$$

This and (A.4-1) imply that $\theta^c > \theta^\alpha \ \forall \phi \neq 0$.

Now, for an arbitrary positive ϕ, define θ^α and θ^c as $\theta^\alpha(\phi)$ and $\theta^c(\phi)$ respectively. Take ϕ' such that $\phi < \phi'$ and $\theta^\alpha(\phi') > \theta^c(\phi)$. As $\theta^c > \theta^\alpha \ \forall \phi \neq 0$, $\theta^c(\phi') > \theta^\alpha(\phi')$. Thus $\theta^c(\phi) < \theta^\alpha(\phi') < \theta^c(\phi')$, which implies that θ^c increases in ϕ. As ϕ and ϕ' were arbitrary, this must hold for all ϕ. Q.E.D.

This lemma suggests that there exists a unique ϕ^c such that $\theta^c \leq 1$ if $\phi \leq \phi^c$ where equality holds only if $\phi = \phi^c$.

Lemma 4-4. $\phi^c < 1$.

Proof. Suppose not, and consider the case where $\phi^c = 1$ and $\gamma \neq 0$. If $\theta = 1 > 1/(1+\gamma)$,

$$z^I = 2(1+\gamma)x^I = z^S = 2(1+\gamma)x^S \text{ at } \theta = 1. \quad (\because \theta^c = \phi^c = 1)$$

This contradicts lemma 4-1.

Next consider the case where $\phi^c > 1$. From $\phi^c > 1 = \theta^c$ and lemma 4-3, there exists ϕ' such that $\phi' = 1 = \theta^c$. Then, substituting $\phi = \phi' = 1$, $\gamma \neq 0$, and $\theta(= \theta^c) = 1$ into z^I and z^S, I get the same outcome as above, a contradiction. Q.E.D.

This lemma suggests that there exists a unique ϕ^c such that $\theta^c \leq 1$ if $\phi \leq \phi^c$ where equality holds only if $\phi = \phi^c$. [70]

Combining the results in three cases, I proved lemma 4-2. Q.E.D.

Proof of proposition 4-1. I use the following.

Lemma 4-5. If $(p^I)' + (p^I)'' z^I < 0 \ \forall\theta$, $d\Pi^I / d\theta > 0 \ \forall\theta$ *if* $p^I \in (0, -\pi^M / 2\Delta\pi] \ \forall\theta$

Proof. Totally differentiating (4-3) w.r.t. x^I and θ and using (4-6), I get

[70] $\theta^c = 1$ only if $\gamma = 0$, $\phi = \phi^c$ or both.

$$\frac{d\Pi^I}{d\theta} = \underbrace{2(1+\gamma)(p^I)'}_{+}\left\{\underbrace{[\phi\pi^M + (1+\phi)\Delta\pi p^I]}_{?}\underbrace{\theta\frac{dx^I}{d\theta}}_{-} + \underbrace{(\pi^M + 2\Delta\pi p^I)}_{?}\underbrace{(1+\phi)x^I}_{+}\right\}. \quad \text{(A.4-4)}$$

When $\pi^M + 2\Delta\pi p^I \geq 0$, the term in curly brackets in (A.4-4) is positive because

$$(\pi^M + 2\Delta\pi p^I) - (\phi\pi^M + (1+\phi)\Delta\pi p^I) = (1-\phi)(p^I\pi^M + (1-p^I)\pi^D) > 0. \quad \text{(A.4-5)}$$

$$dz^I/d\theta = (1+\gamma)(1+\phi)[\theta(dx^I/d\theta) + x^I] > 0 \Rightarrow \left|(1+\phi)x^I\right| > \left|\theta(dx^I/d\theta)\right|. \quad \text{(A.4-6)}$$

This proves the lemma. Q.E.D.

Suppose that $(p^I)' + (p^I)''z^I < 0$ and $p^I \in (0, -\pi^M/2\Delta\pi]\ \forall\theta$. First consider the case where $\theta = \theta^c$. Lemma 4-1 implies that $z^I \geq z^S$ as $1/(1+\gamma) \leq \theta^c$. This leads to $p^I \geq p^S$, which means that the gross profits are no smaller in the *I* regime than in the *S* regime due to (4-8). Since $x^S = x^I$ at $\theta^c = \theta$, this indicates that $\Pi^I \geq \Pi^S$ at $\theta^c = \theta$ where equality holds only if $1/(1+\gamma) = \theta^\alpha = \theta^c$, i.e., $\phi = 0$.

Next consider the case where $\theta = 1/(1+\gamma)$. Then $z^S = z^I$ from lemma 4-1, which means that the gross profits are the same in both regimes. Since $\theta^c \geq 1/(1+\gamma) = \theta$, $x^S \leq x^I$. Hence $\Pi^I \leq \Pi^S$ at $\theta = 1/(1+\gamma)$ where equality holds only if $\phi = 0$.

Because lemma 4-5 holds now, these two results indicate the existence of $\theta_1^{c\Pi}$ such that $\theta_1^{c\Pi} \in [1/(1+\gamma), \theta^c]$ and $\Pi^S > (\leq)\Pi^I$ if $\theta < (\geq)\theta_1^{c\Pi}$. Q.E.D.

Proof of proposition 4-2. The proof is based on the following two lemmas.

Lemma 4-6. $d\Pi^I/d\theta<0 \ \forall\theta$ *if* $p^I \in(-\pi^M/2\Delta\pi,-\pi^M/(1+\phi)\Delta\pi) \ \forall\theta$ *and* ϕ *is large but not 1.*

Proof. Define ϕ=1-ε ($\varepsilon\neq 0$). Substituting this into (A.4), I get

$$\frac{d\Pi^I}{d\theta}=\left(\theta\frac{dx^I}{d\theta}+2x^I\right)(\pi^M+2\Delta\pi p^I)$$

$$-\varepsilon\left\{(\pi^M+2\Delta\pi p^I)x^I+[p^I\pi^D+(1-p^I)\pi^M]\theta\frac{dx^I}{d\theta}\right\}. \quad \text{(A.4-7)}$$

If ε is small, then so is a term in curly brackets in (A.4-7). Then, if $\pi^M+2\Delta\pi p^I<0$, the sign of (A.4-7) is negative due to $\theta(\partial x^I/\partial\theta)+2x^I>0$ from (A.4-6). Q.E.D.

Lemma 4-7. Suppose that $(p^I)'+(p^I)''z^I<0 \ \forall\gamma$.

(a) $d\Pi^I/d\gamma<0 \ \forall\gamma$ *if* $p^I\in(-\pi^M/2\Delta\pi,-\pi^M/(1+\phi)\Delta\pi) \ \forall\gamma$ *and* ϕ *is large.*

(b) $d\Pi^S/d\gamma\geq 0 \ \forall\gamma$ *where equality holds only if* $\phi=0$.

Proof. Totally differentiate (4-3) w.r.t. x^I and γ. Then, substituting (4-6) and ϕ =1-ε ($\varepsilon\neq 0$) into the resultant function, I get

$$d\Pi^I/d\gamma=2\theta(p^I)'\left\{(\pi^M+2\Delta\pi p^I)\left[(1+\gamma)\left(dx^I/d\gamma\right)+2x^I\right]\right.$$

$$-\varepsilon\left[(1+\gamma)(\pi^M+\Delta\pi p^I)\left(dx^I/d\gamma\right)+x^I(\pi^M+2\Delta\pi p^I)\right]\Big\}. \quad \text{(A.4-8)}$$

Applying the implicit function theorem to (4-6), I get

$$\frac{dx^I}{d\gamma}=-\frac{A^I[(p^I)'+z^I(p^I)'']+((p^I)')^2\Delta\pi(1+\phi)z^I}{\theta(1+\phi)(1+\gamma)^2[(p^I)''A^I+((p^I)')^2\Delta\pi(1+\phi)]}<0. \quad \text{(A.4-9)}$$

$$dz^I/d\gamma=\theta(1+\phi)[x^I+(1+\gamma)(dx^I/d\gamma)]>0\Rightarrow\left|(1+\phi)x^I\right|>\left|(1+\gamma)(dx^I/d\gamma)\right|. \quad \text{(A.4-10)}$$

Thus, I can use the same argument as in lemma 4-6. This proves (a).

(b) is straightforward. Applying the implicit function theorem to (4-7), I get

$$dx^S/d\gamma=-2\phi x^S/[1+\phi(1+2\gamma)]\le 0 \quad \forall\gamma. \quad \text{(A.4-11)}$$

$$dz^S/d\gamma=2\phi x^S+[1+\phi(1+2\gamma)](dx^S/d\gamma)=0 \quad \forall\gamma. \quad \text{(A.4-12)}$$

(A.4-12) implies that gross profits remain constant in γ. This and (A.4-11) obviously indicate that $d\Pi^S/d\gamma\ge 0\ \forall\gamma$ where equality holds only if $\phi=0$. Q.E.D.

To prove proposition 4-2, suppose that $\pi^M+2\Delta\pi p^I<0\ \forall\theta$. Note, at first, that (A.4-2) implies that $\Pi^S=\Pi^I$ if $\theta=1$ and $\gamma=0$. This and lemma 4-6 imply that, if $\gamma=0$ and ϕ is large, then $\Pi^S\ge\Pi^I\ \forall\theta$ where equality holds only if $\theta=1$. Now let γ rise arbitrarily from 0. The above result, lemma 4-7(a) and 4-7(b) imply the existence of a critical value, $\theta_2^{c\Pi}$, such that $\Pi^S<(\ge)\Pi^I$ if $\theta_2^{c\Pi}<(\ge)\theta$. Since $z^I=z^S$ and $x^I>x^S$ at $\theta=1/(1+\gamma)$, $\Pi^S>\Pi^I$ there, which means that $\theta_2^{c\Pi}\in(0,1/(1+\gamma)]$. Q.E.D.

Proof of proposition 4-3. I will use the following lemma.

Lemma 4-8. $dW^I/d\theta > 0 \ \forall\theta$ *if* $(p^I)' + (p^I)''z^I < 0 \ \forall\theta$.

Proof. If $(p^I)' + (p^I)''z^I < 0 \ \forall\theta$, total differentiation of (4-9) w.r.t. x^I and θ yields

$$\frac{dW^I}{d\theta} = 4(1+\phi)(1+\gamma)\left[\Delta\omega p^I + (1-p^I)\omega^M\right](p^I)'\left(\theta\frac{dx^I}{d\theta} + x^I\right) - 4\frac{dx^I}{d\theta} > 0$$

$\because \Delta\omega = \omega^D - \omega^M > 0$, (A.4-1) and (A.4-6). Q.E.D.

Following the same steps as those in proposition 4-1 and using (4-10), I proved this proposition. Q.E.D.

Appendix 4-B. [71]

Sah and Stiglitz (1988) (S&S hereafter) considered the situation where firms could choose not only the level of R&D investment for each project but also the number of projects. They showed Strong Invariance Result (SIR hereafter) that not only the investment level per project but also the total number of projects conducted in an industry would be invariant to market structure in equilibrium and claimed that SIR would be a general result.

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[71] This appendix is based on Iidaka (1999.b) and considers the modified I regime where (1) the number of firms is $N\ (\geq 2)$; (2) firms operate in one market only; (3) each firm can choose the number of project $v\ (\geq 1)$; (4) Bertrand competition in a final good market; (5) $\phi = \gamma = 0$, $\theta = 1$.

This appendix incorporates intra-industry spillovers into the model of S&S , which S&S ignored, and shows not only that market structure will affect the R&D investment but also that SIR is not so general as they claim.

In order for that, I set up the model which closely follows S&S. N identical firms (denoted by $i = 1,.., N$) in an industry, which are endowed with the *same* menu of research projects,[72] are engaged in R&D competition. A firm earns R in a market if and only if it alone succeeds in R&D. Otherwise it gets no profits there. Firm i runs v_i parallel projects and invests x_{ij} in project j where $j = 1,.., v_i$ while all other firms undertake v_f parallel projects and invest x_{fs} in project s where $s = 1,.., v_f$. All projects are aimed at the same innovation. Let ϕ denote the rate of spillovers. Then the effective R&D investment in project j by firm i, X_{ij}, is defined as

$$X_{ij} = x_{ij} + \phi(N-1)x_{fj} \quad \text{where } \phi \in [0,1].$$

As S&S did, I assume no spillovers among different projects within a firm (as well as across firms). When $\phi = 0$, my model coincides with that of S&S.

Let $p(X_{ij})$ denote the success probability of project j by firm i where $dp(X_{ij})/dX_{ij} > 0 > d^2p(X_{ij})/d(X_{ij})^2 \ \forall \ X_{ij} \geq 0$. A firm succeeds in R&D if at least one of its projects does. Thus, the probability that firm i succeeds in R&D is

[72] This is purely a simplifying assumption. I think that my result is quite likely to hold even if I assume some difference among firms in their menu.

$$q_i = 1 - \prod_{j=1}^{v_i} \left(1 - p\left(X_{ij}\right)\right) \quad \forall\, i \qquad \text{where } v_i \geq 1.$$

The probability that all other firms fail in R&D is

$$h_i = \prod_{f \neq i} \prod_{s=1}^{v_f} \left(1 - p\left(X_{fs}\right)\right) \qquad \forall\, i.$$

Firm i solves

$$\underset{x_{ij}, v_i}{Max} \;\; \pi_i = q_i h_i R - \sum_{j=1}^{v_i} x_{ij} \qquad \forall\, i.$$

I assume a symmetric interior Nash equilibrium as S&S. Let (x^*, v^*) denote an equilibrium at N. If SIR holds here, any arbitrary $N^\bullet (\neq N)$ must yield an equilibrium, $(x^\bullet, v^\bullet)$, such that $x^\bullet = x^*$ and $Nv^* = N^\bullet v^\bullet = n$ where n is the total number of projects conducted in an industry. Using this, I establish my result.

Proposition. *If $\phi \neq 0$, then SIR does not hold.*

Proof. Suppose not and that SIR holds even if $\phi \neq 0$. At first, I show that SIR implies $X^* = X^\bullet$ where $X^* = [1 + \phi(N - 1)]x^*$ and $X^\bullet = [1 + \phi(N^\bullet - 1)]x^*$. Suppose not and, without loss of generality, that $X^* > X^\bullet (\Leftrightarrow p^* > p^\bullet)$ where $p^* = p(X^*), p^\bullet = p(X^\bullet)$.

The FOC w.r.t. v_i at N is

$$\partial\pi_i/\partial v_i = -\log(1-p^*)R(1-p^*)^n - x^* \approx Rp^*(1-p^*)^n - x^* = 0 \quad \because \text{-log(1-}p\text{)} \approx p.^{73} \quad \text{(B.4-1)}$$

As I am assuming SIR, the following holds true at $N^\bullet$.

$$\partial\pi_i/\partial v_i \approx Rp^\bullet(1-p^\bullet)^{N^\bullet v^\bullet} - x^\bullet = Rp^\bullet(1-p^\bullet)^n - x^* = 0. \quad \text{(B.4-2)}$$

Thus, from (B.4-1) and (B.4-2) ,

$$p^*/p^\bullet = ((1-p^\bullet)/(1-p^*))^n (\neq 1). \quad \text{(B.4-3)}$$

Take an equilibrium, (x^*, v°), at N° such that $N^\bullet \neq N^\circ \neq N$ and

$$p^\circ / p^* = ((1-p^*)/(1-p^\circ))^n = p^*/p^\bullet = ((1-p^\bullet)/(1-p^*))^n \quad \text{(B.4-4)}$$

where $\mathrm{p}^\circ = \mathrm{p}(\mathrm{X}^\circ)$ and $\mathrm{X}^\circ = [1+\phi(\mathrm{N}^\circ - 1)]\mathrm{x}^*$. From (B.4-3) and (B.4-4), I get

$$(p^*)^2 = p^\bullet p^\circ, (1-p^*)^2 = (1-p^\bullet)(1-p^\circ) \Rightarrow (p^\bullet + p^\circ)/2 = p^* \Rightarrow X^* = (X^\bullet + X^\circ)/2. \text{(B.4-5)}$$

However, the assumption that p is strictly concave in X implies that

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[73] Solely for convenience, I treat v as a continuous variable.

$$\left(p^{\bullet}+p^{\circ}\right)/2 = p^{*} \Rightarrow X^{*} = \alpha X^{\bullet} + (1-\alpha)X^{\circ} \text{ where } \alpha \neq 1/2,$$

which contradicts (B.4-5) . Thus $X^{*} = X^{\bullet}$ if SIR holds. This means that

$$X^{*} = X^{\bullet} \Rightarrow \phi(N - N^{\bullet})x^{*} = 0. \qquad \text{(B.4-6)}$$

As $N \neq N^{\bullet}$ and $\phi \neq 0$, (B.4-6) holds only if $x^{*} = 0$, which contradicts an assumption of an interior solution. This completes the proof Q.E.D.

The intuition of this result is as follows. For instance, suppose that $N = 4$ and $N^{\bullet} = 8$. The marginal change in v by a firm affects *via spillovers* the same project of *3* rival at $N = 4$ but *7* rival firms at $N^{\bullet} = 8$. Thus this change is likely to affect more the chance that the firm will be the sole innovator at $N^{\bullet} = 8$ than at $N = 4$. That is, the probability, $p(1-p)^{n-1}$, in (B.4-1) and (B.4-2) is likely differ in two cases when $n = 32$. Thus, x^{*} in (B.4-1) will diverge from that in (B.4-2), which results in breakdown of SIR. Hence, SIR holds only if $\phi = 0$. [74] From this viewpoint, SIR is a rather special case.

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[74] S&S said that the following assumptions would be important for SIR to hold; (1) the success probability of a project conditional on the failure of all other projects is a function solely of the investment on the particular project and the others; (2) every project yields the same rents if it is successful; (3) market competition is Bertrand. My model satisfies all of them. Hence this result was obtained *not* because of violation of an assumption.

Chapter 5. An extended analysis of contractual and in-house R&D

1. Introduction

In this chapter, I will examine profitability and social welfare under the *I* and *S* regimes as well as under the regime where one firm uses Integrated R&D but the other Separated R&D, which I call the Hybrid (*H*) regime.

The model here is similar to the one in Chapter 4 except for two respects. First, I will assume no information leakage across units during R&D. Second, such leakage can occur *after* R&D but it is confined to units involved in the same projects. These assumptions keep the analysis tractable especially in the *H* regime.

After deriving the appropriate results, I will conjecture the impact on profitability and social welfare of the expansion of contractual R&D in the biotechnology industry. Here, I will regard the H (S) regime as the case where there is *partial* (*total*) expansion. Thus, I will examine the impact of partial (total) expansion on market outcomes by comparing the *I* regime with the *H* (*S*) regime.

Section 2 presents the model. Section 3 characterizes an equilibrium in all cases and shows two preliminary results. Sections 4 and 5 examine profitability and social welfare respectively. Section 6 concludes.

2. The model

Two multi-product firms (indexed by $i = 1, 2$) plan to conduct R&D aimed at two *independent* markets (indexed by $k = a, b$). If a firm uses *Integrated R&D*, it runs two parallel projects, *a* and *b*. If it uses Separated R&D, it delegates project *b*

to independent profit maximizing lab j (= i) where $j = 1,2$ while carrying out project a on its own. I assume, for simplicity, that all R&D units are endowed with the same menu of research projects and the same research productivity. If project k is successful, a firm gets a research output transferred either internally or from its lab and reaps in market k the following payoffs:

π^D if both firms obtain a successful research output from project k;

0 if both firms fail to obtain the output from project k;

$\pi^{SF} = (1-\phi)\pi^M + \phi\pi^D$ if the firm *alone* obtains the output from project k;

$\pi^{FS} = \phi\pi^D + (1-\phi)0 = \phi\pi^D$ if its rival firm *alone* obtains the output from the project;

where π^M denotes monopoly profits in market k and ϕ ($\in[0,1]$) is the rate of involuntary information leakage about a *successful* research output. This assumption follows Choi (1992).[75] I make three simplifying assumptions about the leakage. First, information leaks *only* out of a successful R&D unit. Second, once a unit successfully gets an output, it cannot improve the output whatever information it receives from its rival and, thus, increase its profits. Third, information leakage *in effect* occurs only between units involved in project k. For the final output from project k is so specialized that no information about it is relevant to those involved

[75] If $\phi < 1$, an unsuccessful unit costlessly imitates. However, due to the lack of information, the imitation is inferior to the original. Thus the recipient firm of the imitation gets π^{FS} while the firm with the original output earns π^{SF}. If $\phi = 1$, the imitation is as good as the original since the unsuccessful unit gets all the information of the original. Hence both firms earn π^D in market k.

in project k' ($\neq k$).

3. R&D competition

Let p_{uk} denote the probability that unit u succeeds in project k. When firm i uses Integrated R&D, its success probability of project k, p_{ik}, is written as

$$p_{ik} = \theta(e_{ik} + \gamma e_{ik'}) \quad \forall\, i, k \neq k'. \tag{5-1}$$

e_{ik} is the amount of the information in project k. $\gamma e_{ik'}$, $\gamma(\in[0,1])$, and $\theta\in([1/2,1])$ represent the internal spillovers and the size effect respectively as in Chapter 4. These will arise only if a firm runs two projects internally.

Thus, if a firm uses Separated R&D, then its success probability of project a is

$$p_{ia} = e_{ia} \quad \forall i. \tag{5-2}$$

Swapping labels accordingly, I can define the probability of project b by lab j.

I assume well-behaved probability, i.e.

$$e_{uk}, p_{uk} \in [0,1) \quad \forall\, (u, k) = (i, k) \text{ and } (j, b).$$

Moreover, the success probability is independent across projects and all R&D outcomes are publicly revealed at the end of this stage.

To produce the amount of the information, e_{uk}, unit u has to invest $x(e_{uk})$ in

project k with the following properties;

$$\text{(i) } dx(e_{uk})/de_{uk} = x'(e_{uk}) > 0, d^2x(e_{uk})/d(e_{uk})^2 = x''(e_{uk}) > 0 \ \forall e \in (0,1);$$

$$\text{(ii) } x'(0) = x(0) = 0; \text{ (iii) } x'(e_{uk}) \to \infty \text{ as } e_{uk} \to 1.$$

(i) says that x_{uk} is strictly convex in e_{uk}. (ii) implies that unit u does not produce any information at all without investment while (iii) suggests that it is not possible for the unit to produce $e_{uk} = 1$ with a finite amount of investment.

When *both* firms use Integrated R&D (the *I* regime), firm i solves

$$\underset{e_{ia}, e_{ib}}{Max} \quad \Pi_i = [p_{ia}(1-p_{i'a}) + p_{ib}(1-p_{i'b})]\pi^{SF} + [p_{ia}p_{i'a} + p_{ib}p_{i'b}]\pi^{D}$$

$$+ [p_{i'a}(1-p_{ia}) + p_{i'b}(1-p_{ib})]\pi^{FS} - x(e_{ia}) - x(e_{ib}) \quad \forall i \neq i' \quad (5\text{-}3)$$

If *both* firms use Separated R&D (the *S* regime), firm i and lab j solve respectively

$$\underset{e_{ia}}{Max} \ \Pi_i = p_{ia}(1-p_{i'a})\pi^{SF} + p_{ia}p_{i'a}\pi^{D} + (1-p_{ia})p_{i'a}\pi^{FS} - x(e_{ia}) + F \quad \forall i \neq i'; \quad (5\text{-}4)$$

$$\underset{e_{jb}}{Max} \ \Pi_j = p_{jb}(1-p_{j'b})\pi^{SF} + p_{jb}p_{j'b}\pi^{D} + (1-p_{jb})p_{j'b}\pi^{FS} - x(e_{jb}) - F \ \forall j \neq j'. \quad (5\text{-}5)$$

F is firm i's profits from project b (*net* of the research fee paid to its partner lab) and, for simplicity, is assumed to be exogenous and to solve $\Pi_j = 0$ in equilibrium.

If firm i uses Integrated R&D and firm i' Separated R&D, which I call the *H* regime, firm i maximizes (5-3), and firm i' and lab j' (5-4) and (5-5) respectively.

There p_{ik} is given by (5-1) while $p_{i'a}$ and $p_{j'b}$ are by (5-2).

Thus, defining $\Delta\pi = \pi^{DU} - \pi^{SF} - \pi^{FS} \leq 0$, I get the following FOCs:

$$\partial\Pi^{I}/\partial e = \theta(1+\gamma)(\pi^{SF} + \Delta\pi p^{I}) - x'(e^{I}) = 0 \tag{5-6}$$

$$\partial\Pi^{S}/\partial e = (\pi^{SF} + \Delta\pi p^{S}) - x'(e^{S}) = 0 \tag{5-7}$$

$$\partial\Pi^{IH}/\partial e = \theta(1+\gamma)(\pi^{SF} + \Delta\pi p^{SH}) - x'(e^{IH}) = 0 \tag{5-8}$$

$$\partial\Pi^{SH}/\partial e = (\pi^{SF} + \Delta\pi p^{IH}) - x'(e^{SH}) = 0 \tag{5-9}$$

Superscripts I and S refer to an equilibrium in the I and the S regimes respectively. IH and SH represents an equilibrium under Integrated R&D and Separated R&D in the H regime respectively. As the $x'(0) = 0$, FOCs imply that an interior solution always exists. Moreover, I can easily verify that the SOCs are always satisfied.

Using these FOCs, I obtain two preliminary results. The first one is as follows.

Lemma 5-1. *Let* $\alpha = \pi^{SF} + \Delta\pi(\theta(1+\gamma)+1)e^{S}$. *If* $\gamma > (<)\ (1-\theta)/\theta$ *and* $\alpha \begin{Bmatrix} \geq \\ < \end{Bmatrix} 0$,

$e^{SH} < (>) \begin{Bmatrix} e^{S} \leq (\geq) e^{I} \\ e^{I} < (>) e^{S} \end{Bmatrix} < (>) e^{IH}$ *where equality holds iff* $\alpha = 0$. *If* $\gamma = (1-\theta)/\theta$,

$e^{SH} = e^{I} = e^{S} = e^{IH}$.

The intuition of the result is as follows. If γ is large, i.e., $\gamma > (1-\theta)/\theta$, this encourages a unit under Integrated R&D to set a large e. For, the unit internalize a positive externality via cross fertilization, and a large γ means a larger externality effect. On

Figure 5-1(a)

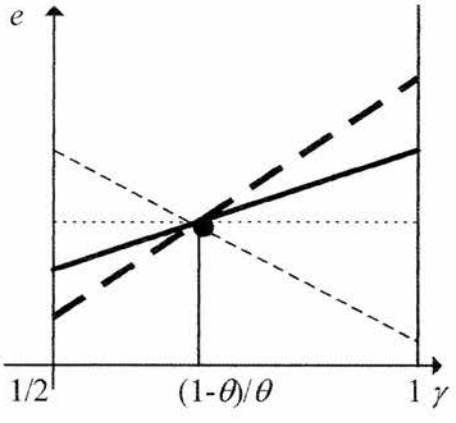


Figure 5-1(b)

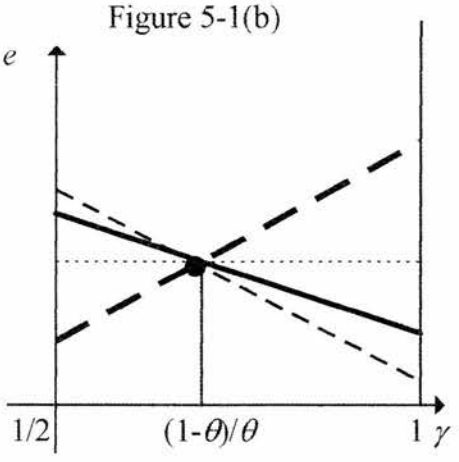


Figure 5-1(c)

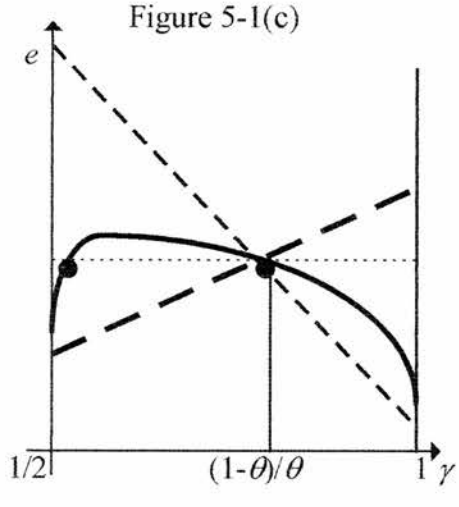
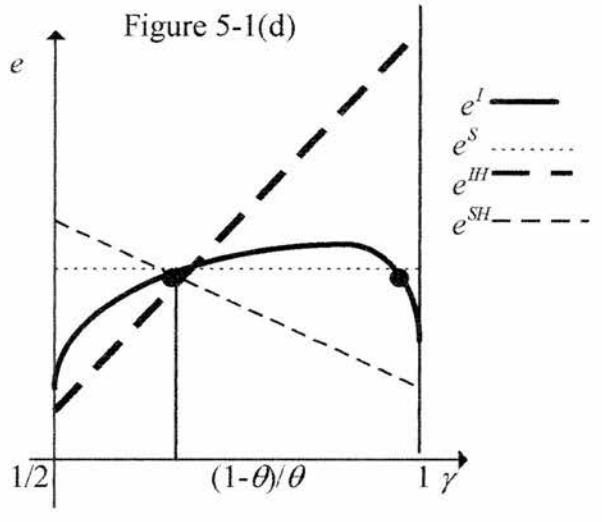
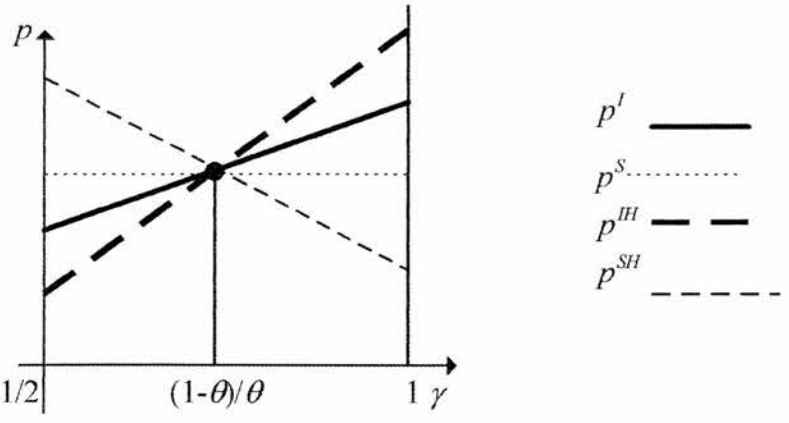


Figure 5-1(d)



the contrary, the unit whose *rival* uses Integrated R&D is discouraged to set a large e. Note that $\pi^{SF} + \Delta\pi p$ in marginal revenues is the difference between the payoff for successful R&D, $\pi^{SF}(1-p) + \pi^{D}p$, and that for unsuccessful R&D, $\pi^{FS}p$. Given some e, a large γ leads to the small difference between them, which makes the unit less eager to get the former payoff and, thus, less keen to set a large e. Here, a unit under Integrated (Separated) R&D in the H regime faces only the positive (negative) effect while in the I (S) regime it would face both (neither). This intuitively suggests that the unit under Integrated (Separated) R&D in the H regime sets the largest (smallest) e. The result says that if and only if $\alpha > (=) 0$,

Figure 5-2



the positive effect dominates (cancels out) the negative one so that $e^I > (=) e^S$.

If γ is small, i.e. $\gamma < (1-\theta)/\theta$, this discourages a unit under Integrated R&D to set a large e. For, though the positive externality effect is still present, it is small so that the size effect, θ, which works *against* the positive effect, outweighs that. However, the unit whose rival uses Integrated R&D would set a large e. For a small γ enlarges the above payoff difference, which induces the unit to get the payoff for successful R&D by setting a large e. Hence, a unit under Separated (Integrated) R&D in the H regime will set the largest (smallest) e among all. Moreover, if and only if $\alpha > (=)$ 0, the negative effect dominates the positive one so that $e^I < (=) e^S$. If $\gamma = (1-\theta)/\theta$, all FOCs are identical, and, thus, so are all outcomes.

Then, the second preliminary result is

Lemma 5-2. If $\gamma \geq (<)(1-\theta)/\theta$, $p^{SM} \leq (>) p^S \leq (>) p^I \leq (>) p^{IH}$ *where all equalities hold iff* $\gamma = (1-\theta)/\theta$.

Figure 2 illustrates the result. It says that, if γ is small, the success probability is

higher under Separated R&D than under Integrated R&D, and *vice versa*. A small γ means that little can be gained from cross fertilization. Due to this and the size effect, a unit under Integrated R&D assimilates a smaller amount of information for a project than a unit under Separated R&D. This results in the lower probability by the former. When γ is large, there is much to be gained from cross fertilization. Thus, in spite of the size effect, the above result is reversed. The difference between p^S and p^{SH} (between p^I and p^{IH}) is entirely due to the difference between e^S and e^{SH} (between e^I and e^{IH}).

4. Comparison of profits.

Using the above results, I compares firm profits in each case. There are two points in the result. First, a firm can always earn larger profits with the organization which produces the *higher* success probability. Second, if the success probability at $\gamma = (1-\theta)/\theta$ is relatively *low (high)*, a firm can earn larger profits if its rival firm uses the organization which produces the *higher* (*lower*) success probability.

Note that here a firm can sometimes benefit from the higher success probability of its rival firm (and its partner). This situation does not arise in the literature on RJVs with spillovers (except for Choi (1992) and Katsoulacos and Ulph (1998)). Now, for the sake of argument, take the success probability in our model as a R&D output. In the literature, the larger R&D output, i.e. the larger effective investment, of a rival firm simply decreases gross profits of a given firm. For the rival shifts rents from the given firm by lowering its own marginal cost (via the larger R&D output). On the contrary, in my model the larger output of a rival affects gross

profits of a given firm in two ways with opposite effects. It lowers the payoff of success, $(1-p)\pi^{SF} + p\pi^{D}$, while raising that of failure, $p\pi^{FS}$. If the latter outweighs the former, the higher probability of the rival can raise gross profits of the given firm.

This has an interesting implication when I advance a conjecture on the impact of the expansion of contractual R&D on profitability in the biotechnology industry. As in the previous chapter, the outcomes of the conjecture depend on the degree of competition in a final good market and the nature of R&D. However, the expansion can lead to either a Pareto improvement or Prisoner's dilemma, depending on the impact of the rival firm's success probability on profits of a given firm.

Below I will present these results in detail.

Using the preliminary results, I establish my first main result. Define e^* as the equilibrium amount of information per project at $\gamma = (1-\theta)/\theta$.

Proposition 5-1. Suppose that $\pi^{FS} + \Delta\pi e^* \leq 0$. *Then*

$$\left.\begin{array}{l} \Pi^{IM} > max\{\Pi^{I}, \Pi^{S}\} \geq min\{\Pi^{I}, \Pi^{S}\} > \Pi^{SM} \\ \Pi^{IM} < min\{\Pi^{I}, \Pi^{S}\} \leq max\{\Pi^{I}, \Pi^{S}\} < \Pi^{SM} \end{array}\right\} \text{ if } \gamma \left\{\begin{array}{l} > \\ < \end{array}\right\} (1-\theta)/\theta \text{ and } \gamma \text{ is close}$$

to $(1-\theta)/\theta$. *Either only one of equalities holds or neither holds. All profit level are identical when* $\gamma = (1-\theta)/\theta$.

Proposition 5-2. Suppose that $\pi^{FS} + \Delta\pi e^*$ *is positive but small. Then*

$$\left.\begin{array}{l} \Pi^{I} > max\{\Pi^{IM}, \Pi^{SM}\} > min\{\Pi^{IM}, \Pi^{SM}\} > \Pi^{S} \\ \Pi^{I} < min\{\Pi^{IM}, \Pi^{SM}\} < max\{\Pi^{IM}, \Pi^{SM}\} < \Pi^{S} \end{array}\right\} \text{ if } \gamma \left\{\begin{array}{l} > \\ < \end{array}\right\} (1-\theta)/\theta \text{ and } \theta \text{ is}$$

close to $(1-\theta)/\theta$. *All profit levels are identical when* $\gamma = (1-\theta)/\theta$.

Figure 5-3(a)

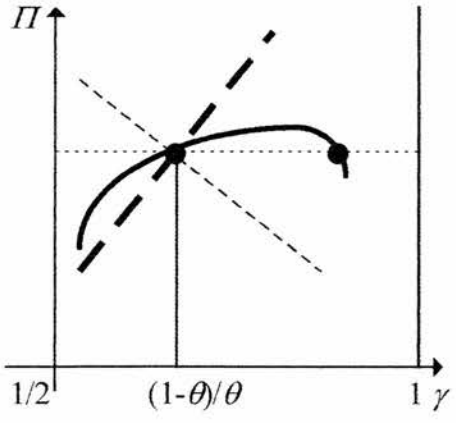


Figure 5-3(b)

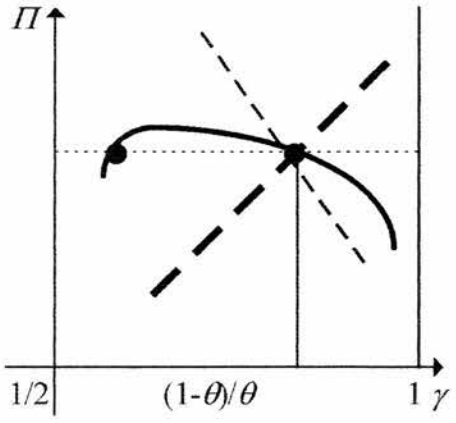
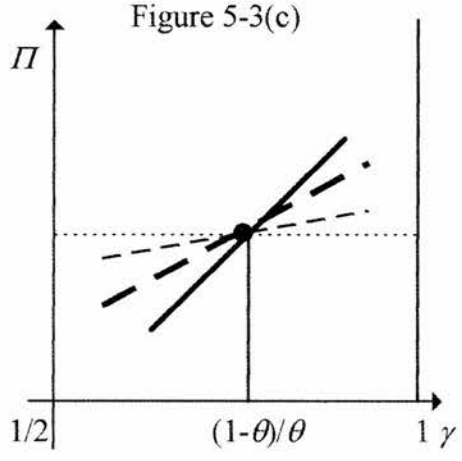


Figure 5-3(c)



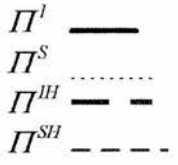


Figure 5-3 (a) (5-3 (b)) illustrates proposition 5-1 where $\Pi^I = \Pi^S$ at $\gamma = (1-\theta)/\theta$ and $\gamma > (<) (1-\theta)/\theta$ while Figure 5-3 (c) depicts proposition 5-2 where $max\{\Pi^{IH}, \Pi^{SH}\} = \Pi^{SH}(\Pi^{IH})$ at $\gamma > (<) (1-\theta)/\theta$.

Propositions 5-1 and 5-2 consider the cases where e^* is relatively large (small) or where the success probability is relatively high (low) around $\gamma = (1-\theta)/\theta$.

These results are driven mainly by the behavior of gross profits. Note

$$d[p_i(p_{i'}\pi^D + (1-p_{i'}\pi^{SF})) + (1-p_i)p_{i'}\pi^{FS}]/dp_i = \pi^{SF} + p_{i'}\Delta\pi > 0. \qquad (5\text{-}10)$$

$$d[\,p_i(p_{i'}\pi^D+(1-p_{i'}\pi^{SF}))+(1-p_i)p_{i'}\pi^{FS}\,]/dp_{i'}=\pi^{FS}+p_i\Delta\pi\gtrless 0. \qquad (5\text{-}11)$$

The intuition of (5-10) is simple. When p_i goes up, firm i is more likely to earn $p_{i'}\pi^D+(1-p_{i'})\pi^{SF}$ than $p_{i'}\pi^{FS}$, and the former is larger than the latter. Thus, gross profits of firm i go up with the higher p_i. The intuition of (5-11) is as follows. When p_i is relatively high, firm i is likely to get $p_{i'}\pi^D+(1-p_{i'})\pi^{SF}$. The higher $p_{i'}$ lowers $p_{i'}\pi^D+(1-p_{i'})\pi^{SF}$, which decreases gross profits for firm i. Conversely, when p_i is relatively low, firm i will earn $p_{i'}\pi^{FS}$. As a higher $p_{i'}$ raises $p_{i'}\pi^{FS}$, it will increase gross profits of firm i.

The profit comparison depends on the sign of (5-11).

First, consider the case where $\pi^{FS}+\Delta\pi e^*\le 0$. (5-10), (5-11), and lemma 5-2 suggest that gross profits in $\Pi^{SH}(\Pi^{IH})$ is the largest (smallest) if $\gamma<(1\text{-}\theta)/\theta$ while the reverse holds if $\gamma>(1\text{-}\theta)/\theta$. Note that for gross profits in a symmetric regime,

$$d[\,p(p\pi^D+(1-p)\pi^{SF})+(1-p)p\pi^{FS}\,]/dp=\pi^{SF}+\pi^{FS}+2p\Delta\pi\gtrless 0. \quad (5\text{-}12)$$

This says that whether gross profits in Π^S are larger than those in Π^I depends on whether p^S is closer to $-(\pi^{SF}+\pi^{FS})/2\Delta\pi$ than p^I is. These comparisons lead to proposition 5-1 irrespective of the level of aggregate investment.

Next consider the case where $\pi^{FS}+\Delta\pi e^*>0$. Then $\Pi^I(\Pi^S)$ is the largest if $\gamma>(<)\ (1\text{-}\theta)/\theta$. The reason is that the success probability of a rival firm (and its partner lab) has a larger impact on profits of a given firm than its own (and its partner lab's) probability. For instance, take profits of firm i' in the H and the S

regimes and, purely for the sake of argument, suppose that the regime changes from the H to the S. When $\gamma < (1-\theta)/\theta$, firm i' and lab j' achieve lower success probability in the S regime than in the H regime (i.e., $p^{SH} > p^{S}$). According to (11), this has an adverse effect on gross profits of firm i'. However, firm i and its partner lab j yields the higher probability in the S regime (i.e., $p^{S} > p^{IH}$), which (11) says means the larger gross profits of firm i' with the regime change. Here, the latter positive effect outweighs the former negative one. Thus, firm i' will earn larger gross (and net) profits to firm in the S regime. If $\gamma > (1-\theta)/\theta$, the relationship in the probability between the H regime and the S regime is reversed and, thus, so is the result.

For later reference, let us examine further the case of $\gamma < (1-\theta)/\theta$. If both firms use (or switch to) Separated R&D, proposition 5-1 says that the outcome can be viewed as a consequence of Prisoner's Dilemma if $\Pi^{I} > \Pi^{S}$ This can arise if p^{S} makes (5-12) negative and $|p^{S} - [-(\pi^{SF} + \pi^{FS})/2\Delta\pi]| > |p^{I} - [-(\pi^{SF} + \pi^{FS})/2\Delta\pi]|$. The intuition is that the success probability is higher in the S regime than in the I regime so that firms are more likely to face competition in downstream markets in the S regime. That dissipates their profits there.

Conversely, proposition 5-2 shows that the resultant S regime Pareto dominates the other cases, which can happen if both ϕ and π^{D} are non-trivial. Here, if a firm changes to Separated R&D, it boosts its own and its partner's success probability and, thus, firm's gross profits (due to (5-10)). Also, such a boost in the probability raises gross profits of its rival firm (due to (5-11)) via the rise in the expected failure payoff, $p(1-p)\pi^{FS}$. This makes the S regime the Pareto dominant configuration.

What distinguishes a Prisoner's Dilemma case from a Pareto dominant one is the impact of the expected failure payoff via ϕ. The change to Separated R&D by a firm increases its expected success payoff, $p(\pi^{SF}(1-p)+\pi^{D}p)$, at the expense of that of its rival firm. However the change lowers its failure payoff, $p(1-p)\pi^{FS}$, while raising that of its rival. In the Prisoner's Dilemma case ϕ is small and, thus, so is the impact of the expected failure payoff. Thus, the above organizational change affects only the expected success payoff and only the firm that switches to Separated R&D becomes better off at the expense of its rival firm. On the other hand, in the Pareto dominant case, ϕ is non-trivial and, thus, so is the impact of the expected failure payoff on profits. The result shows that the impact is small enough for the net profits of the switching firm to go up but large enough for those of the other firm to go up.

I am now in a position to use the propositions to advance a conjecture on whether the expansion of contractual R&D in the biotechnology industry will result in the higher profitability. Note that the H (S) can be viewed as the case where there is *partial* (*total*) expansion of the contractual R&D so that some (all) firms use contractual R&D while the I regime as the case where there is no expansion. Thus, I will examine the impact of partial (total) expansion on profitability by comparing the I regime with H (S) regime.

Using some estimates of key variables in the model taken from the empirical literature on industrial biotechnology, I can determine which of my propositions applies to the industry. Here, the success probability of R&D and the presumption that $\gamma < (1-\theta)/\theta$ are the same as Chapter 4. As I have no information on ϕ, I assume

that either $\phi = 0$ or $\phi = 1/2$. [76] Also, due to the same problem, I will consider two polar cases for the profitability of downstream markets separately: the competitive Bertrand duopoly yielding zero profits and the less competitive Cournot duopoly. Let us assume for simplicity that firms face a linear demand function and have constant marginal costs. In the Bertrand case, $\pi^D = 0$ so that $-\pi^{FS} / \Delta\pi = 0$ while in the Cournot case, $\pi^D = 4\pi^M / 9$ so that $-\pi^{FS} / \Delta\pi = 4/9$ (0) if $\phi = 1/2$ (0).

First, in the Bertrand case, partial expansion results in larger (smaller) profits for firms under contractual (in-house) R&D while total expansion will lead to smaller profits for all firms. As $-\pi^{FS} / \Delta\pi = 0 < 0.0125$ and 0.53, proposition 5-1 applies here. When there is no expansion, all firms achieve the success probability, p^I, while with partial expansion, units under contractual (in-house) R&D achieve the success probability, p^{SH} (p^{IH}), which is higher (lower) than p^I. This, (5-10), and (5-11) suggest that partial expansion will result in larger (smaller) profits of a firm under contractual (in-house) R&D. However, with total expansion, all units generate the success probability, p^S, which is higher than p^I. Its consequence rests on whether R&D is for a standard product and a novel one. Note that $0.0125 < -(\pi^{SF} + \pi^{FS})/2\Delta\pi = 0.5 < 0.53$. This and (5-12) indicate that in a standard product case, p^S is too large relative to the probability which maximizes gross profits while p^S is closer to the probability than p^I is in a novel product case. As a result of this, total expansion will lead to smaller (larger) profits if R&D

[76] Since Integrated R&D and Separated R&D is, in effect, non-cooperative R&D, ϕ is presumably small as mentioned in fn. 64 in Chapter 4. For the sake of simplicity, I assume that $\phi = 0$ or $\phi = 1/2$.

is for standard (novel) products. [77]

In the Cournot case, if $\phi = 0$ or if $\phi = 1/2$ *and* R&D is for novel products, partial (total) expansion will lead to the same outcome as the above partial expansion case (the above novel product case in total expansion). For, as $0.0125 < -\pi^{FS} / \Delta\pi = 4/9$ (if $\phi = 1/2$) and $-\pi^{FS} / \Delta\pi = 0 < 0.0125$ and 0.53 (if $\phi = 0$), proposition 5-1 applies to these cases. Here, total expansion results in larger profits. For, if $\phi = 1/2$ (0), then $-(\pi^{SF} + \pi^{FS})/2\Delta\pi = 17/18$ (9/10), which is larger than 0.0125 and 0.53.

If $\phi = 1/2$ *and* R&D is for standard products, the expansion, whether partial or total, will lead to larger profits for *all* firms. For, as $-\pi^{FS} / \Delta\pi = 4/9 < 0.53$, proposition 5-2 applies. As mentioned earlier, with expansion of contractual R&D, whether partial or total, a firm and a lab under contractual R&D achieve the success probability p^{SH} (in partial expansion) or p^{S} (in total expansion), which are higher than p^{I}. Here, unlike in other cases, a firm under contractual R&D can benefit other firms with these higher probabilities as (5-11) suggests.

The above discussions about the biotechnology industry were based on the result of duopoly case, but the industry is quite often characterized as N (> 2) firm oligopoly. This gap raises the question about robustness of our assessments of the biotechnology industry. As N rises, a critical value, $-\pi^{FS} / \Delta\pi$, is likely to be

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[77] A standard product case can be likened to Prisoner's Dilemma. If the expansion is partial, firms can earn larger profits under contractual R&D at the expense of those under in-house R&D. However, if the expansion is total, too many firms (and labs) achieve too high success probability and, thus, firms are more likely to face fierce competition in a final good market, which dissipates their expected profits. In this case, they can be better off if they all collusively remain to use in-house R&D.

replaced with some smaller value. That could alter some of the above assessments.

5. Welfare comparisons

This section compares social welfare in each regime. The outcome depends on two probabilities: the one that market k will be duopoly and the one that it will be monopoly. The high probability of duopoly has a positive impact on social welfare as it means the high chance of competition in a market, which leads to the large expected gross welfare. The high probability of monopoly too contributes to the large gross welfare. For, as shown later, the high probability makes it likely that a final good market will enjoy some surplus rather than no surplus at all. My result shows that welfare is the largest in the regime when the probability of duopoly is the highest. However, welfare is the second largest in the regime where the probability of monopoly is the highest. Intriguingly, in this regime the probability of duopoly is lower than in the regime where welfare is the smallest. This interestingly implies that the regime with the higher prospect of *monopoly* is socially preferable to the one with the higher prospect of *duopoly*.

I also find that social welfare is on the whole larger when Integrated R&D is more productive, i.e. produces the higher success probability than Separated R&D with some e given. It is presumably because in the latter case the probability of duopoly will be higher (so that competition in a market is more likely) than in the former. [78]

In the previous chapter I mentioned that the importance for welfare of the information assimilation ability of units (rather than competitiveness in R&D) .

[78] Nothing certain can be said about the probability of monopoly.

This applies here, too, under some circumstances.

I also advance a conjecture on whether the expansion of contractual R&D will lead to larger welfare. I will show that, whether partial or total, the expansion will result in large welfare.

The rest of the section shows these results in detail.

Let ω^M and ω^D denote social welfare in market k when monopoly and when both firms obtain a *successful* research output from project k respectively. Moreover,

let $\omega^{SF}(=(1-\phi)\omega^M+\phi\omega^D)$ denote social welfare there when only one firm obtains a successful output. Then, in the symmetric regime r ($=I, S$) and the H regime, social welfare can be written respectively as

$$W^r = 2[2p^r(1-p^r)\omega^{SF} + p^r p^r \omega^D - 2x(e^r)]. \quad (5\text{-}13)$$

$$W^H = 2[(p^{IH}(1-p^{SH}) + p^{SH}(1-p^{IH}))\omega^{SF} + p^{IH}p^{SH}\omega^D - x(e^{IH}) - (e^{SH})]. \quad (5\text{-}14)$$

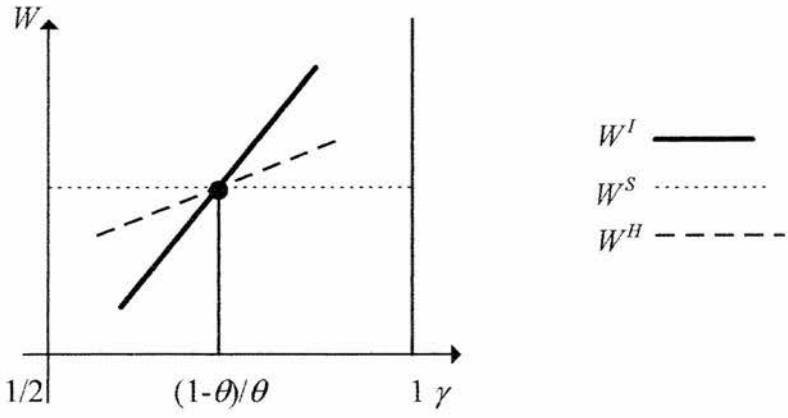
Proposition 5-3. If γ is close to (1-θ)/θ, $W^I \gtrless W^H \gtrless W^S$ if $\gamma \gtrless (1-\theta)/\gamma$.

Equalities hold only if γ = (1-θ)/θ.

Figure 5-4 illustrates proposition 2. It says that welfare is the largest (smallest) in the S (I) regime if γ is smaller than (1-θ)/θ, but the reverse holds otherwise. [79]

[79] As to the comparison between the I regime and the S regime, what I said in the previous chapter applies here as it is if $\pi^{SF} + 2\Delta\pi e^* < 0$.

Figure 5-4



Two comments about this result are in order. First it shows that, if $\gamma<(>)\ (1-\theta)/\theta$ and a firm changes to Separated (Integrated) R&D, that brings social benefits. However the reason differs according to which regime results from the organizational change. To show that, suppose that the regime changes from the *I* regime to the *H* regime at $\gamma < (1-\theta)/\theta$. Then the success probability of firm *i'* (and lab *j'*) goes up while that of firm *i* down. This makes monopoly by firm *i'* in a final good market more likely but duopoly less likely. [80] Roughly speaking, the higher probability of monopoly means the lower probability that both units involved in project *k* fail. [81] Due to this, society is more likely to enjoy some surplus in this regime (albeit via monopoly) than in the *I* regime, which results in the larger welfare in the *H* regime. Next, suppose another regime change from the *H* regime

[80] Note that if γ is close to $(1-\theta)/\theta$, the probability in all regimes is not so different. Let $p^{IH} = p^r - \varepsilon_1$ and $p^{SH} = p^r + \varepsilon_2$ where $\varepsilon_1 \approx \varepsilon_2 \approx \varepsilon$, ε is small, and p^r is the probability in the symmetric regime *r*. Then $2p^r(1-p^r)-[1-(p^r-\varepsilon)](p^r+\varepsilon)-[1-(p^r+\varepsilon)](p^r-\varepsilon)<0$ and $p^r p^r-(p^r-\varepsilon)(p^r+\varepsilon)>0$.

[81] The probability that both units in project *k* fail is $(1-p)(1-p)=-p^M+(1-p)$ where p^M is the probability of monopoly. This intuitively suggests that the larger p^M lowers the probability.

to the S regime. The resultant success probability among units raises (lowers) the probability of duopoly (monopoly) as shown in fn. 79. Here, this higher probability of duopoly will be the factor which boosts social welfare. Applying a similar argument, I can find out how a change to Integrated R&D by a firm increases social welfare at $\gamma > (1-\theta)/\theta$.

Second, social welfare is on the whole larger when Integrated R&D is more efficient, i.e. $\gamma > (1-\theta)/\theta$, than when Separated R&D is, i.e., $\gamma < (1-\theta)/\theta$. That is, from the viewpoint of social welfare cross fertilization is preferable to the specialization effect. The reason is that the probability of duopoly is larger at $\gamma > (1-\theta)/\theta$ than at

$\gamma < (1-\theta)/\theta$ so that a final good market is more likely to be competitive in the former. To show that, let us take the I regime at $\gamma < (1-\theta)/\theta$ and the S regime at $\gamma > (1-\theta)/\theta$. Now suppose that one firm changes its organization in each case, which leads to the H regime. This change enhances social welfare due to the specialization effect (much cross fertilization) at $\gamma < (>) (1-\theta)/\theta$. However, if I compare social welfare in both cases, it is larger at $\gamma > (1-\theta)/\theta$ since the probability of duopoly is likely to be higher there. [82] If I let the H regime change to the S (I) regime at $\gamma < (>) (1-\theta)/\theta$, welfare increases to $W^S (W^I)$. One can check that the reason of the increase in social welfare and the result about the probability of duopoly are the same as above.

The result indicates that the expansion of contractual R&D in the biotechnology industry, whether partial or total, would lead to the larger welfare regardless of the nature of R&D and downstream markets. However, at the same time, the expansion

would make worse market failure caused by externalities if $\pi^{SF} + 2\Delta\pi e^{*} < 0$.[83] This has a perverse policy implication for the government which seeks a socially first best outcome with R&D subsidy as in Leahy and Neary (1997). For, though the expansion results in the *larger* welfare, such a government has to provide *more* subsidy when there is the expansion than when there is not.

On the other hand, if $\pi^{SF} + 2\Delta\pi e^{*} > 0$, it is possible that the expansion could not only result in the larger welfare but also the less distortion. However, I cannot identify the circumstance where such a desirable situation could occur.

6. Conclusion

This chapter examined the implications of in-house R&D organization and contractual R&D organization for profitability and social welfare. Whereas welfare differences can be attributed solely to their organizational structure, profit comparisons depend not only on the choice of organization that but also on the success probability of a project. On the basis of the results, I advanced some conjectures on the impact on market outcomes of the expansion of contractual R&D in the biotechnology industry. The expansion, whether partial or total, is likely to result in larger welfare. Whether it will lead to the higher profitability will depend on three factors, namely, the spillover rate, the degree of competitiveness of downstream markets, and whether R&D is aimed for novel products or standard products.

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[82] See Appendix 5-C.

[83] See Appendix 5-D.

This and the previous chapter assumed that industry structure was exogenously fixed. However, I have demonstrated in Chapters 4 and 5 that it will make a difference to profits for a firm whether to use in-house R&D or contractual R&D. Thus it is reasonable to think that whether firms use in-house R&D or contractual R&D could influence industry structure by affecting their profits.

Chapter 2 showed that an increasing number of large multi-product firms came to rely on contractual R&D in the biotechnology industry since the 80s.

The question of my interest is whether such expansion of contractual R&D could reduce industry concentration by affecting profitability. To examine this issue and the welfare implication of the expansion of contractual R&D, the next chapter will extend our framework to a more general oligopoly case.

Appendix A.

Proof of lemma 5-1. Evaluating (5-6) at $e = e^S$ and using (5-7), I get

$$\partial \Pi^I / \partial e \big|_{e=e^S} = [\theta(1+\gamma) - 1][\pi^{SF} + \Delta\pi(\theta(1+\gamma)+1)e^S]$$

Define $\pi^{SF} + \Delta\pi(\theta(1+\gamma)+1)e^S$ as α. Then,

$$\partial \Pi / \partial e \big|_{e=e^S} \left\{\begin{matrix}\geq \\ < \end{matrix}\left(\begin{matrix}\leq \\ > \end{matrix}\right)\right\} 0 \Leftrightarrow e^I \left\{\begin{matrix}\geq \\ < \end{matrix}\left(\begin{matrix}\leq \\ > \end{matrix}\right)\right\} e^S \text{ if } \gamma > (<)\ (1-\theta)/\theta \text{ and } \alpha \left\{\begin{matrix}\geq \\ < \end{matrix}\right\} 0. \qquad \text{(A.5-1)}$$

Substituting e^I into (5-8) and (5-9) and, then, using (5-6), I obtain

$$\partial \Pi^{IH} / \partial e \big|_{e=e^I} = \theta(1+\gamma)(\pi^{SF} + \Delta\pi e^I) - x'(e^I) = [1 - \theta(1+\gamma)]\Delta\pi p^I. \qquad \text{(A.5-2)}$$

$$\partial \Pi^{SH} / \partial e \big|_{e=e^I} = (\pi^{SF} + \Delta\pi\theta(1+\gamma)e^I) - x'(e^I) = [1 - \theta(1+\gamma)][\pi^{SF} + \Delta\pi p^I]. \qquad \text{(A.5-3)}$$

Consider the case where $\gamma < (1-\theta)/\theta$. Then, (A.5-2) is non-positive as $\Delta\pi \leq 0$ while (A.5-3) is positive as $\pi^{SF} + \Delta\pi p^I > 0$. Thus firm i reduces its e^I on both projects to e^{IH_1} to make (A.5-2) equal to 0 while (given this change) firm i' and lab j' raise their e^I to, say, e^{SH_1} so that (A.5-3) holds. Then, (A.5-2) becomes negative, which induces firm i to lower e^{IH_1} to e^{IH_2} on both projects to make (A.5-2) equal to 0. Then (A.5-3) becomes negative so that e^{SH_1} will go up to e^{SH_2}, which makes (A.5-3) equal to 0. This iterative process continues. Thus

$$\cdots\cdots\cdots e^{IH_2} < e^{IH_1} < e^{I} < e^{SH_1} < e^{SH_2} \cdots\cdots\cdots$$

The series generated by this process is monotonic. Since e is bounded and closed by definition, the limiting e, which I define as e^{IH} and e^{SH}, must be such that

$$e^{IH} < e^{I} < e^{SH} \qquad \text{(A.5-4)}$$

If $\gamma > (1-\theta)/\theta$, then (A.5-2) is non-negative and (A.5-3) negative. Hence the situation is exactly opposite to the above, and it can be easily proved that

$$e^{SH} < e^{I} < e^{IH}. \qquad \text{(A.5-5)}$$

The comparison between e^{S}, e^{IH} and e^{SH} can be made in the same way. Substituting e^{S} into (5-8) and (5-9) and using (5-7), I get

$$\partial \Pi^{IH} / \partial e \big|_{e=e^{S}} = \theta(1+\gamma)(\pi^{SF} + \Delta\pi e^{S}) - x'(e^{S}) = [\theta(1+\gamma) - 1](\pi^{SF} + \Delta\pi e^{S}). \quad \text{(A.5-6)}$$

$$\partial \Pi^{SH} / \partial e \big|_{e=e^{S}} = (\pi^{SF} + \Delta\pi\theta(1+\gamma)e^{S}) - x'(e^{S}) = [\theta(1+\gamma) - 1]\Delta\pi e^{S}. \qquad \text{(A.5-7)}$$

If $\gamma < (>) (1-\theta)/\theta$, (A.5-6) is positive (negative) while (A.5-7) is non-positive (non -negative) so that the above technique yields

$$e^{IH} < (>) e^{S} < (>) e^{SH}. \qquad \text{(A.5-8)}$$

If $\gamma = (1-\theta)/\theta$, then all the four FOCs become identical, which results in

$$e^S = e^I = e^{IH} = e^{SH}. \qquad \text{(A.5-9)}$$

(A.5-1), (A.5-4), (A.5-5), (A.5-8), and (A.5-9) prove the proposition. Q.E.D.

Proof of lemma 5-2. If $\gamma \geq (1-\theta)/\theta$, i.e. $\theta(1+\gamma) \geq 1$, then lemma 5-1 implies that

$$e^{SH} \leq \min\{e^I, e^S\} \leq \max\{e^I, e^S\} \leq e^{IH}$$

$$\Rightarrow \; e^{SH} = p^{SH} \leq \min\{p^I, p^S\} \leq \max\{p^I, p^S\} \leq \theta(1+\gamma)e^{IH} = p^{IH}. \qquad \text{(A.5-10)}$$

where equality holds only if $\gamma = (1-\theta)/\theta$. If $\gamma < (1-\theta)/\theta$, I can verify that all inequalities in (A.5-10) are reversed. Lemma 5-1 and (B.5-4) in Appendix 5- B imply that

$$p^S < (\geq) p^I \text{ if } \gamma > (\leq) (1-\theta)/\theta.$$

This completes the proof. Q.E.D.

Proof of Proposition 5-1 and 5-2. As a preliminary, I use the following.

Lemma 5-3. Let e^* be the equilibrium amount of information per project at $\gamma = (1-\theta)/\theta$. (a) $d(\Pi^I - \Pi^{SH})/d\gamma\big|_{\gamma=(1-\theta)/\theta} > 0$ unless $\pi^{FS} + \Delta\pi e^*$ is very large.

(b) $d(\Pi^{I} - \Pi^{IH})/d\gamma\big|_{\gamma=(1-\theta)/\theta} \geq (<)0$ *if* $\pi^{FS} + \Delta\pi e^{*} \geq (<)0$ *where equality hold only if* $\pi^{FS} + \Delta\pi e^{*} = 0$.

Proof. Totally differentiating Π^{I} w.r.t. γ and e^{I}, and of Π^{IH} and Π^{SH} w.r.t. γ, e^{IH} and e^{SH}, and substituting the results in Appendix 5-B, I get

$$\frac{d\Pi^{I}}{d\gamma} = \underbrace{\frac{2\theta}{x'' - (\theta(1+\gamma))^{2}\Delta\pi}}_{+}\left\{\underbrace{x''e^{I}(\pi^{SF} + 2\Delta\pi p^{I})}_{+\;\;?} + \underbrace{\pi^{FS}[\theta(1+\gamma)(\pi^{SF} + \Delta\pi p^{I}) + x''e^{I}]}_{+}\right\}. \quad \text{(A.5-11)}$$

$$\frac{d\Pi^{IH}}{d\gamma} = \underbrace{\frac{2\theta}{|H|}}_{+}\left\{\underbrace{\Delta\pi}_{-}\underbrace{(\pi^{FS} + \Delta\pi p^{IH})}_{?}\underbrace{[\theta(1+\gamma)(\pi^{SF} + \Delta\pi p^{SH}) + x''(e^{IH})e^{IH}]}_{+}\right.$$

$$\left. + \underbrace{e^{IH}(\pi^{SF} + \Delta\pi p^{SH})|H|}_{+}\right\}. \quad \text{(A.5-12)}$$

$$d\Pi^{SH}/d\gamma = \underbrace{2\theta[(1+\gamma)(de^{IH}/d\gamma) + e^{IH}]}_{+}\underbrace{(\pi^{FS} + \Delta\pi p^{SH})}_{?}. \quad \text{(A.5-13)}$$

where $|H| = x''(e^{IH})x''(e^{SH}) - (\theta(1+\gamma)\Delta\pi)^{2} > 0$. (See fn. 84 for |H|). Since $\pi^{SF} + \Delta\pi e^{*}$ is marginal revenues of a unit at $\gamma = (1-\theta)/\theta$, which is positive, I get

$$\frac{d(\Pi^{I} - \Pi^{SH})}{d\gamma}\bigg|_{\gamma=\frac{1-\theta}{\theta}} = \underbrace{\frac{2\theta}{|H|}}_{+}\left\{\underbrace{e^{*}|H|(\pi^{SF} + \Delta\pi e^{*})}_{+} + \underbrace{\Delta\pi}_{-}\underbrace{(\pi^{SF} + \Delta\pi e^{*} + x''e^{*})}_{+}\underbrace{(\pi^{FS} + \Delta\pi e^{*})}_{?}\right\}. \quad \text{(A.5-14)}$$

$$d(\Pi^{I} - \Pi^{IH})/d\gamma\Big|_{\gamma=\frac{1-\theta}{\theta}} = \underbrace{(2x''\theta/|H|)}_{+}\underbrace{(\pi^{FS} + \Delta\pi e^{*})}_{?}\underbrace{(\pi^{SF} + \Delta\pi e^{*} + x''e^{*})}_{+}. \quad \text{(A.5-15)}$$

(A.5-14) and (A.5-15) imply lemma 5-3 (a) and (b) respectively. Q.E.D.

In addition to this result, note two facts. First, profits are the same under all regimes at $\gamma = (1-\theta)/\theta$ due to lemma 5-1 and 5-2. Second, $\Pi^I = \Pi^S$ can hold both at $\gamma = (1-\theta)/\theta$ and at $\gamma \neq (1-\theta)/\theta$ if $\pi^{FS} + \Delta\pi p^I < 0$. [84] For instance, if $\phi = 0$, $\alpha = 0$ at $\gamma <(>)$ $(1-\theta)/\theta$, and $p^S(p^I) \leq 1/2$ at the γ, there exists $\gamma (<(>)(1-\theta)/\theta)$ where $\Pi^I = \Pi^S$. With these two facts and lemma 5-3, I proved proposition 5-1 and 5-2. Q.E.D.

Proof of proposition 5-3. Totally differentiating (5-13) w.r.t. γ and e^I, and using the result in Appendix 5-B, I get

$$\frac{dW^I}{d\gamma} = \underbrace{\frac{4\theta}{x'' - (\theta(1+\gamma))^2 \Delta\pi}}_{+} \left\{ \underbrace{e^I x'' \omega}_{+} + \underbrace{\theta(1+\gamma)(\pi^{SF} + \Delta\pi p^I)}_{+} \underbrace{[\omega - (\pi^{SF} + 2\Delta\pi p^I)]}_{?} \right\}. \quad \text{(A.5-16)}$$

where $\omega = (\omega^D - \omega^{SF})p^I + (1-p^I)\omega^{SF} > 0$. As $\omega^D > \omega^{SF}$ and $\omega^{SF} > \pi^{SF}$,

$$\begin{aligned} \omega - (\pi^{SF} + 2\Delta\pi p^I) &= (\omega^D - \omega^{SF})p^I + (\omega^{SF} - \pi^{SF})(1-p^I) + p^I(\pi^{SF} - 2\pi^D + 2\pi^{FS}) \\ &= (\omega^D - \omega^{SF})p^I + (\omega^{SF} - \pi^{SF})(1-p^I) + p^I[(1-\phi)\pi^M + (3\phi - 2)\pi^D] \\ &\geq \underbrace{(\omega^D - \omega^{SF})p^I}_{+} + \underbrace{(\omega^{SF} - \pi^{SF})(1-p^I)}_{+} + \underbrace{p^I[(1-\phi)2\pi^D + (3\phi-2)\pi^D]}_{+/0} > 0 \end{aligned}$$

Thus, (A.5-16) is positive for all γ.

Next, totally differentiating (5-14) w.r.t. γ, e^{IH} and e^{SH}, substituting the results in Appendix 5-B and evaluating of the derivative and (A.5-16) at $\gamma = (1-\theta)/\theta$, I get

[84] If $\pi^{FS} + \Delta\pi p^I \geq 0 \ \forall\gamma$, I can verify that (A.5-11) is positive so that $\Pi^I = \Pi^S$ at $\gamma = (1-\theta)/\theta$.

$$dW^H/d\gamma\Big|_{\gamma=(1-\theta)/\theta} = 2\{(\omega - x')[(de^{IH}/d\gamma)+(de^{SH}/d\gamma)]+\theta e^*\}$$
$$= \frac{2\theta}{x''-\Delta\pi}\left[\omega\pi^{SF} - (\pi^{SF}+2e^*\Delta\pi)x' + \omega e^*(x''+\Delta\pi)\right]. \quad \text{(A.5-17)}$$
$$= (1/2)\left(dW^I/d\gamma\Big|_{\gamma=(1-\theta)/\theta}\right)$$

(A.5-17) and the fact that $W^I = W^H = W^S$ at $\gamma = (1-\theta)/\theta$ lead to proposition 5-3.

Q.E.D.

Appendix 5-B. Applying the implicit function theorem to (5-6), I get

$$de^I/d\gamma = [\theta(\pi^{SF} + 2\Delta\pi p^I)]/[x''(e^I) - (\theta(1+\gamma))^2\Delta\pi] \quad \text{(B.5-1)}$$

$$\frac{dp^I}{d\gamma} = \theta e^I + \theta(1+\gamma)\frac{de^I}{d\gamma} = \frac{\theta[\theta(1+\gamma)(\pi^{SF} + p^I\Delta\pi) + e^I x'']}{x'' - (\theta(1+\gamma))^2\Delta\pi} > 0 \quad \forall\gamma. \quad \text{(B.5-2)}$$

Totally differentiating (5-8) and (5-9) w.r.t. e^{IH}, e^{SH}, and γ, I get

$$\begin{pmatrix} de^{IH}/d\gamma \\ de^{SH}/d\gamma \end{pmatrix} = -\frac{\theta}{|H|}\begin{pmatrix} -x''(e^{SH}) & -\theta(1+\gamma)\Delta\pi \\ -\theta(1+\gamma)\Delta\pi & -x''(e^{IH}) \end{pmatrix}\begin{pmatrix} \pi^{SF} + \Delta\pi p^{SH} \\ \Delta\pi e^{IH} \end{pmatrix} \quad \text{(B.5-3)}$$

where $|H| = x''(e^{IH})x''(e^{SH}) - (\theta(1+\gamma)\Delta\pi)^2$.

To find the sign of $de^{IH}/d\gamma$ and $de^{SH}/d\gamma$, suppose that γ goes up slightly. Given e^{IH} and e^{SH}, this makes (5-8) positive but (5-9) negative. Using the method of lemma 5-1, I can get $e^{IH'} > e^{IH}$ and $e^{SH'} > e^{SH}$ where $e^{IH'}$ and $e^{SH'}$ are the limiting

e here. As γ was arbitrary, this holds for all γ. Thus $de^{IH}/d\gamma > 0 > de^{SH}/d\gamma \ \forall\gamma$.[85]

Appendix 5-C.

Let γ_1 and γ_2 be such that $\gamma_1 < (1-\theta)/\theta < \gamma_2$,

$|\gamma_1 - (1-\theta)/\theta| = |\gamma_2 - (1-\theta)/\theta|$, and they are not far away from $\gamma = (1-\theta)/\theta$.

Using (B.5-3), I get

$$\left.\frac{dp^{IH}}{d\gamma}\right|_{\gamma=\frac{1-\theta}{\theta}} + \left.\frac{dp^{SH}}{d\gamma}\right|_{\gamma=\frac{1-\theta}{\theta}} = \theta(1+\gamma)\left(\left.\frac{de^{IH}}{d\gamma}\right|_{\gamma=\frac{1-\theta}{\theta}}\right) + \theta e^{*} + \left.\frac{de^{SH}}{d\gamma}\right|_{\gamma=\frac{1-\theta}{\theta}} \qquad \text{(C.5-1)}$$
$$= \left[\theta/(x'' - \Delta\pi)\right](\pi^{SF} + e^{*}\Delta\pi + e^{*}x'') > 0$$

Lemma 5-2 and (C.5-1) indicates that

$$p^{IH}\big|_{\gamma=\gamma_1} < p^{SH}\big|_{\gamma=\gamma_2} \text{ and } p^{SH}\big|_{\gamma=\gamma_1} < p^{IH}\big|_{\gamma=\gamma_2} \Rightarrow p^{IH}p^{SH}\big|_{\gamma=\gamma_1} < p^{IH}p^{SH}\big|_{\gamma=\gamma_2}.$$

Appendix 5-D.

Let e^{I^*}, e^{S^*} and a pair of e^{IH^*} and e^{SH^*} denote a maximizer of social welfare function in the I, the S and the H regime respectively. Using the technique of proof for lemma 5-1, I can verify that

[85] Note that this result and the sign of each element in the RHS matrix imply that $|H| > 0 \ \forall\gamma$.

$$e^{SH^*} > max\{e^{S^*}, e^{I^*}\} > min\{e^{S^*}, e^{I^*}\} > e^{IH^*}$$

$$\Rightarrow x^{SH^*} > max\{x^{S^*}, x^{I^*}\} > min\{x^{S^*}, x^{I^*}\} > x^{IH^*} \qquad \text{(D.5-1)}$$

If $\pi^{SF} + 2\Delta\pi e^* < 0$, then using lemma 5-1 and (B.5-1), I get $x^I > x^S$ if $\gamma < (1-\theta)/\theta$.

Since externalities yield a socially inefficient outcome,

$$0 < min\{x^{I^*} - x^I, x^{S^*} - x^S\} < max\{x^{I^*} - x^I, x^{S^*} - x^S\}.$$

if $\gamma < (1-\theta)/\theta$. Now let $x^{IH^*} = x^{I^*} - \varepsilon_1$ and $x^{SH^*} = x^{I^*} + \varepsilon_2$ where $\varepsilon_1, \varepsilon_2 > 0$. If $\pi^{SF} + 2\Delta\pi e^* < 0$, then (B.5-1) and (B.5-3) lead to

$$2\left(de^I/d\gamma\big|_{\gamma=(1-\theta)/\theta}\right) > de^{SH}/d\gamma\big|_{\gamma=(1-\theta)/\theta} + de^{IH}/d\gamma\big|_{\gamma=(1-\theta)/\theta} > 0 \Rightarrow 2x^I > x^{IH} + x^{SH}. \quad \text{(D.5-2)}$$

Thus using (D.5-2) and setting $\varepsilon_1 \approx \varepsilon_2 \approx \varepsilon$, I obtain

$$(x^{SH^*} - x^{SH}) + (x^{IH^*} - x^{IH}) \approx 2x^{I^*} - (x^{IH} + x^{SH}) > 2(x^{I^*} - x^I) > 0. \qquad \text{(D.5-3)}$$

Using the similar arguments, I can show that if $\pi^{SF} + 2\Delta\pi e^* < 0$,

$$2(x^{S^*} - x^S) > (x^{SH^*} - x^{SH}) + (x^{IH^*} - x^{IH}) > 0. \qquad \text{(D.5-4)}$$

Hence, if $max\{x^{I^*} - x^I, x^{S^*} - x^S\} = x^{S^*} - x^S$, the change from the I regime to the H regime to the S regime results in more distortion.

Chapter 6. R&D organizations and industry structure

1. Introduction

This chapter examines the relationship between R&D organizations and industry structure, and the impact of the resultant industry structure on social welfare.

A very noticeable change which biotechnology brought to the biotechnology industry in the 80s was a reduction in industry concentration *at the R&D stage*. In Chapter 2 I showed that large multiproduct firms, which were equipped with biotechnology, diversified their in-house R&D into fields removed from their traditional expertise. The most notable example was substantial entry into the pharmaceutical industry by non-pharmaceutical firms.

However, the recent expansion of contractual R&D means that nowadays these multiproduct firms are often involved in R&D in several industries via contractual R&D. For instance, a chemical firm runs a project for chemical development on its own but delegates a project for drug development to an independent lab in the pharmaceutical industry.

I will examine whether such use of contractual R&D could facilitate further a reduction in concentration. To this end, I will consider two cases: the Integrated (I) regime where there is no contractual R&D so that all N^I firms rely on their in-house R&D and the Separated (S) regime where there is *total* expansion of contractual R&D so that all N^S firms use contractual R&D. Then I will investigate whether N^I is greater than N^S in free entry equilibrium. Studying how the structure of industries will be affected by R&D organization, I will also

analyze the resultant social welfare of the industries.

Unlike in Chapter 4 and 5, I incorporate the impact of industry structure on social welfare into the analysis. Moreover, the subsequent conjecture on the impact of the expansion of contractual R&D will take into account this effect of industry structure.

In addition to the two symmetric regimes, I will briefly analyze the Hybrid (H) regime where *some* firms use contractual R&D. By comparing the I regime with the H regime I will be able to assess the impact of *partial* expansion of contractual R&D on industry structure and social welfare.

Section 2 presents the model. Section 3 analyzes R&D competition under contractual R&D and in-house R&D. Section 4 examines the resultant industry structure. Section 5 investigates social welfare under the equilibrium industry structures. Section 6 discusses extensions. Section 7 concludes.

2. The model.

N multiproduct firms (indexed by $i = 1,.., N$) plan to conduct R&D aimed at two *independent* markets (indexed by $k = a, b$). If firm i uses *Integrated R&D*, then it runs two parallel projects, a and b. If it uses *Separated R&D*, it delegates project b to independent profit maximizing lab j ($= i$) where $j = 1,.., N$ while carrying out project a on its own. I assume, for simplicity, that all R&D units are endowed with the same menu of research projects and the same research productivity. If project k is successful, then a firm gets a research output (either transferred internally or from its lab) and reaps in market k either the payoff π^M if the firm *alone* introduces a new product there or the payoff 0 if it fails to introduce the product or

it faces Bertrand competition with some other firm. The Bertrand assumption is purely to simplify the analysis.

3. R&D competition

Let p_{uk} denote the probability that unit u succeeds in project k. When firm i uses Integrated R&D, its success probability of project k, p_{ik}, is written as

$$p_{ik} = \theta(e_{ik} + \gamma e_{ik'}) \quad \forall\ i, k \neq k'. \tag{6-1}$$

e_{ik} is the amount of the information in project k. $\theta \in [1/2,1]$ is the size parameter and $\gamma e_{ik'}$, ($k' \neq k$ and $\gamma \in [0,1]$) is the spillover resulting from cross fertilization.

If firm i uses Separated R&D, then its success probability of project a is

$$p_{ia} = e_{ia} \quad \forall i. \tag{6-2}$$

Swapping labels accordingly, I can define the probability of project b by lab j.

I assume well-behaved probability, i.e.

$$e_{uk}, p_{uk} \in [0,1) \quad \forall\ (u, k) = (i, k) \text{ and } (j, b).$$

Moreover, success probability is independent across projects and all R&D outcomes are publicly revealed at the end of this stage.

To produce the amount of information, e_{uk}, unit u has to invest $x(e_{uk})$ in project

k with the following properties:

Assumption 1. (i) $dx(e_{uk})/de_{uk} = x'(e_{uk}) > 0, d^2x(e_{uk})/d(e_{uk})^2 = x''(e_{uk}) > 0$

$\forall e_{uk} \in (0,1)$; (ii) $x'(0) = x(0) = 0$; (iii) $x'(e_{uk}) \to \infty$ as $e_{uk} \to 1$.

When all firms use Integrated R&D (the I regime), firm i solves

$$\underset{e_{ia}, e_{ib}}{Max} \quad \Pi_i = \left[p_{ia}(1-p_{i'a})^{N-1} + p_{ib}(1-p_{i'b})^{N-1}\right]\pi^M - x(e_{ia}) - x(e_{ib}) \quad \forall i \neq i'. \quad (6\text{-}3)$$

If they use Separated R&D (the S regime), firm i and lab j solve respectively

$$\underset{e_{ia}}{Max} \quad \Pi_i = p_{ia}(1-p_{i'a})^{N-1}\pi^M - x(e_{ia}) + F_S \quad \forall i \neq i'; \quad (6\text{-}4)$$

$$\underset{e_{jb}}{Max} \quad \Pi_j = p_{jb}(1-p_{j'b})^{N-1}\pi^M - x(e_{jb}) - F_S \quad \forall j \neq j'. \quad (6\text{-}5)$$

F_S is firm i's profits from project b (*net* of the research fee paid to its partner lab) and, for simplicity, is assumed to be exogenous and to solve $\Pi_j = 0$ in equilibrium.

I confine the analysis to these two symmetric cases, reserving the analysis of the asymmetric case for Section 6. The FOCs are

$$\partial\Pi^I/\partial e = \pi^M\theta(1+\gamma)(1-p^I)^{N-1} - x'(e^I) = 0. \quad (6\text{-}6)$$

$$\partial\Pi^S/\partial e = \pi^M(1-p^S)^{N-1} - x'(e^S) = 0. \quad (6\text{-}7)$$

Figure 6-1(a)

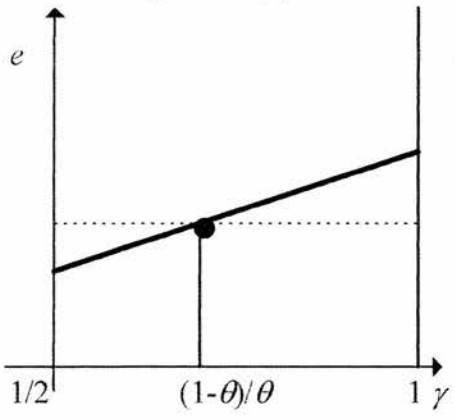


Figure 6-1(b)

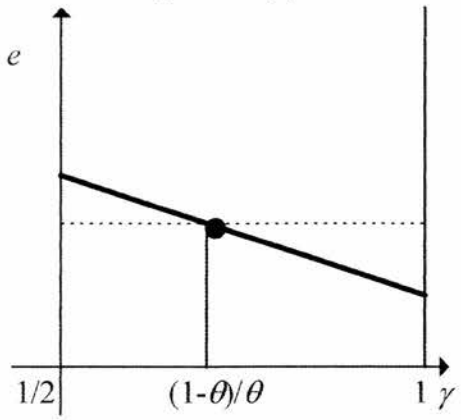


Figure 6-1(c)

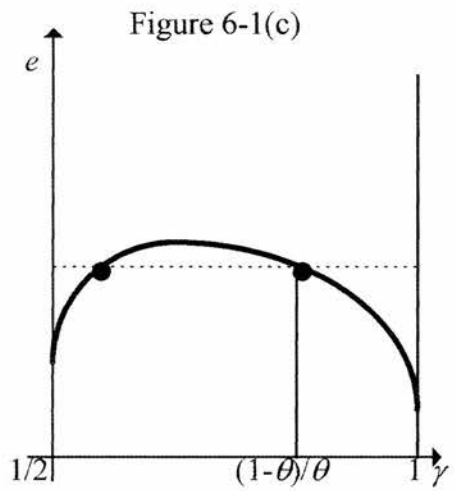
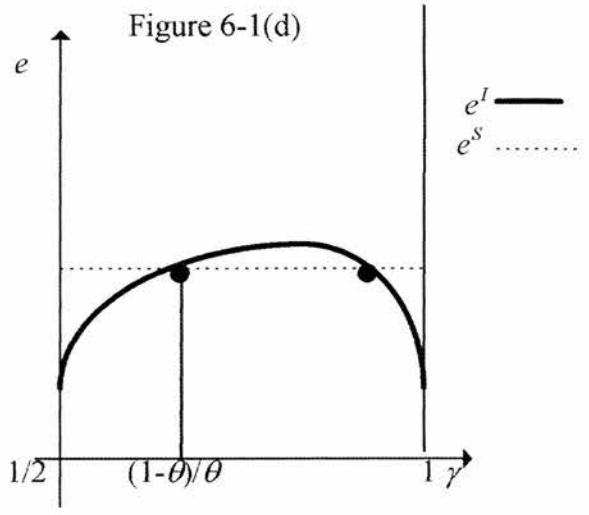


Figure 6-1(d)



Superscripts I and S refer to an equilibrium in the I and the S regimes respectively. As $x'(0) = 0$, an interior solution exists. Moreover, the SOC are always satisfied. I will get two preliminary results from these FOCs.

Lemma 6-1. *Let* $\alpha = 1 - e^S \sum_{h=1}^{N} \left((\theta(1+\gamma))^{\frac{1}{N-1}} \right)^{N-h}$. *If* $\alpha > (<) \; 0$ *and* $\gamma \gtrless (1-\theta)/\theta$, *then* $e^I \gtrless (\lesseqgtr) e^S$. *If* $\alpha = 0$, $e^I = e^S$.

The result is illustrated in Figure 6-1, [86] and its intuition is as follows. If γ is large, i.e. $\gamma > (1-\theta)/\theta$, this induces a unit to set a larger e in the I regime than in the S regime. For, in the former case a unit internalizes a positive externality via cross fertilization, and a large γ means a larger externality effect. However, a large γ has an opposite effect on e as well. For, given e, the payoff for the successful R&D, $\pi^M(1-p)^{N-1}$, is smaller in the former case than in the latter. Iff $\alpha > (=) 0$, the positive effect outweighs (cancels out) the negative one so that $e^I > (=) e^S$. If γ is small, i.e.

$\gamma < (1-\theta)/\theta$, this induces a unit to set a smaller e in the I regime. For, though the positive externality effect is present, it is small so that the size effect, θ, which works *against* the positive effect, outweighs it. However, given e, a small γ makes the success payoff larger in the I regime. Iff $\alpha > (=) 0$, the negative effect dominates (cancels out) the positive one so that $e^I < (=) e^S$. If $\gamma = (1-\theta)/\theta$, both FOCs are identical, and, thus, so are all outcomes.

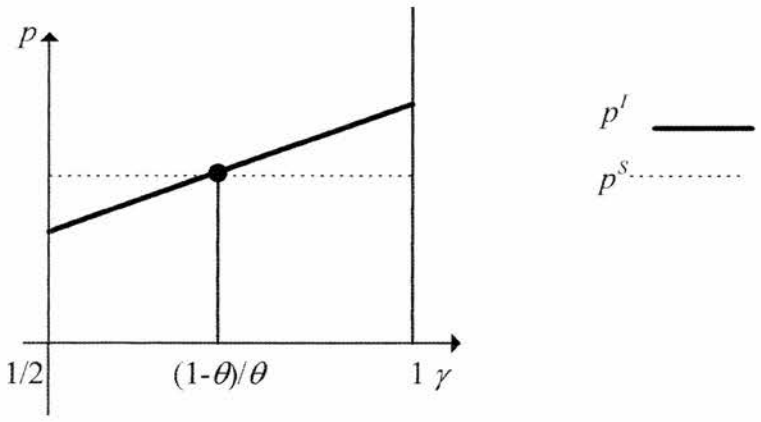
The second preliminary result will be used extensively throughout the analysis.

Lemma 6-2. $p^I \gtreqless p^S$ *if* $\gamma \gtreqless (1-\theta)/\theta$.

This is illustrated in Figure 6-2. It says that if γ is smaller than $(1-\theta)/\theta$, the success probability is higher in the S regime than in the I regime, and *vice versa*. A small γ

[86] Figure 6-1(a) to 6-1(d) illustrate some possible results.

Figure 6-2



means that little can be gained from cross fertilization in the *I* regime. Due to this and the size effect, a unit assimilates the smaller amount of information for a project in the *I* regime, which results in the lower probability of success in the *I* regime. When γ is large, there is much to be gained from cross fertilization. Thus, in spite of the size effect, the unit assimilates the larger amount of information for a project in the *I* regime, which leads to the higher probability in the *I* regime.

4. Comparison of industry structure.

Using the results derived in the previous section, I will compare industry structure under two regimes by comparing profitability there. The key relationship is between the probability p^I and $1/N^I$. If p^I is small (large) relative to $1/N^I$, there will be more entry in the regime where units generate the higher (lower) success probability. It is because of the behavior of gross profits.

This and lemma 6-1 imply that if the probability is high, there will be more entry in the case where units act more competitively and/or have the less efficient output

Cournot competition. There, more competitive behavior and/or the inefficient production process (e.g. a high production marginal cost) dissipate profits [87] so that *fewer* firms can operate in such a situation. The key of our result is the information assimilation process of units. If the process is inefficient, the large investment due to fierce R&D competition does not result in the high success probability. This not-so-high probability benefits firms, for it reduces the chance that many units succeed, which prevents market competition from becoming too fierce and, thus, expected profits from being dissipated. As a result, more firms can enter viably.

Using the above results, I advance a conjecture on whether total expansion of contractual R&D will result in more concentration. The outcome turns out to depend on the nature of R&D.

Below I will present these results in detail.

Proposition 6-1. Define $\Delta = |p^I - (1/N)| - |p^S - (1/N)|$.

(a) If $p^I < 1/N \ \forall \gamma$ *and* $\gamma \lesseqgtr (1-\theta)/\theta$ *, then* $\Pi^I \lesseqgtr \Pi^S$

(b) If $p^I > 1/N \ \forall \gamma$ *and* $\gamma \lesseqgtr (1-\theta)/\theta$ *, then* $\Pi^I \gtreqless \Pi^S$

(c) If $\exists \gamma_1 (\in [0,(1-\theta)/\theta))$ *s.t., at* γ_1*, both* $\alpha = 0$ *and* Δ *is either positive o negative but close to 0, then* $\exists \gamma_{\Pi_1} \in [0,(1-\theta)/\theta)$ *s.t.* $\Pi^I = \Pi^S$ *at* $\gamma = \gamma_{\Pi_1}$*. Thus,* $\Pi^I = \Pi^S$ *if* $\gamma = (1-\theta)/\theta$ *or* $\gamma = \gamma_{\Pi_1}$*;* $\Pi^I > \Pi^S$ *if* $\gamma \in (\gamma_{\Pi_1}, (1-\theta)/\theta))$*;* $\Pi^I < \Pi^S$ *otherwise.*

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[87] Bonanno and Vickers (1988) show that the higher marginal cost can boost profits.

Figure 6-3(a)

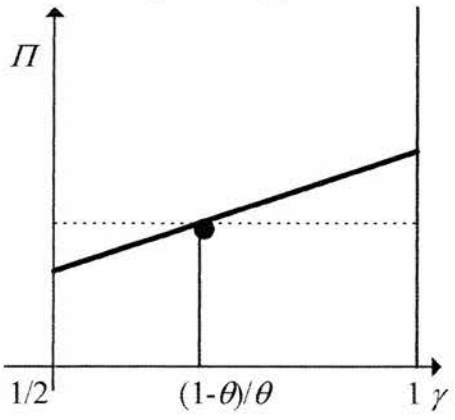


Figure 6-3(b)

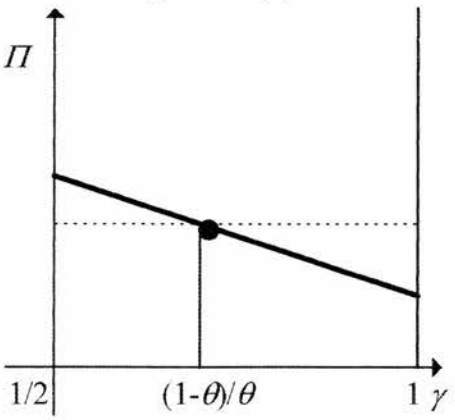


Figure 6-3(c)

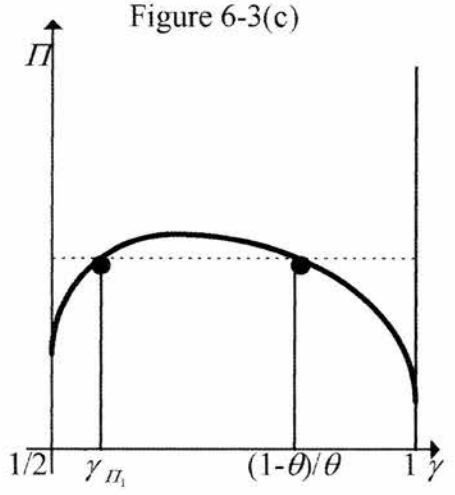
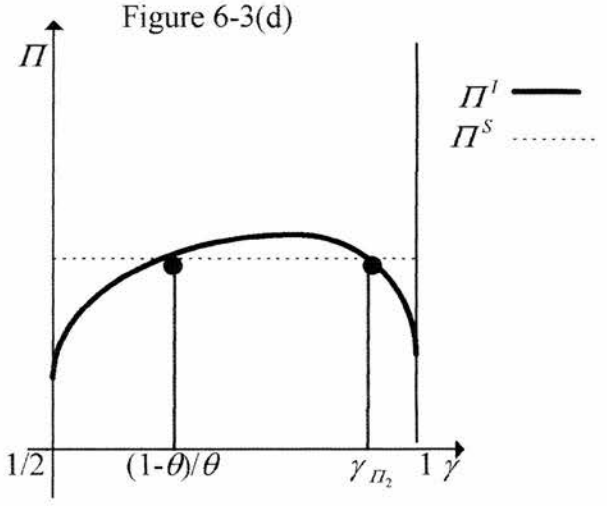


Figure 6-3(d)



(d) If $\exists \gamma_2 (\in((1-\theta)/\theta,1))$ *s.t., at* γ_2, *both* $\alpha = 0$ *and* Δ *is either positive or negative but close to 0, then* $\exists \gamma_{\Pi_2} \in((1-\theta)/\theta,1]$ *s.t.* $\Pi^I = \Pi^S$ *at* $\gamma = \gamma_{\Pi_2}$. *Thus,*

$\Pi^I = \Pi^S$ *if* $\gamma = (1-\theta)/\theta$ *or* $\gamma = \gamma_{\Pi_2}$; $\Pi^I > \Pi^S$ *if* $\gamma \in((1-\theta)/\theta), \gamma_{\Pi_2})$;

$\Pi^I < \Pi^S$ *otherwise.*

The results are illustrated in Figure 6-3(a) to 6-3(d) respectively.

Here, the organization which can produce the probability closer to $1/N$ yields larger net profits. (It is so even if it often induces units to invest more heavily than the other). For, gross profits, which determine the result, are uniquely maximized

at $p = 1/N$. [88] Both organizations produce a probability lower than $1/N$ in case (a). Thus, the organization which achieves the higher probability yields larger profits. In (b), both generate a probability higher than $1/N$. Hence, the organization which yields the lower probability produces larger profits. In (c), if γ is small, $p^S > 1/N > p^I$. [89] Here, the assumption about Δ ensures that p^S is closer to $1/N$ than p^I is. However, as γ gets larger, this becomes reversed at $\gamma \in (\gamma_{\Pi_1}, (1-\theta)/\theta)$. [90] If $\gamma > (1-\theta)/\theta$, the logic of (b) applies since $p^I > p^S > 1/N$. In (d), if $\gamma < (1-\theta)/\theta$ ($\gamma > \gamma_{\Pi_2}$), both yield a lower (higher) probability than $1/N$, and, thus, arguments in (a) ((b)) apply here. The case where $\gamma \in ((1-\theta)/\theta, \gamma_{\Pi_2})$ is essentially the same as an intermediate γ case in (c).

Let g be the exogenous cost of entry. Let us assume that $\Pi^r - g = 0$ *at* N^r in *free entry equilibrium* and that $N^{r'} > N^r$ ($r \neq r'$) if $\Pi^{r'} - g > \Pi^r - g = 0$ at N^r. [91]

Corollary 6-1. Define $\Delta = |p^I - (1/N^I)| - |p^S - (1/N^I)|$.

(a) If $p^I < 1/N^I$ $\forall \gamma$ *and* $\gamma \lesseqgtr (1-\theta)/\theta$, *then* $N^I \lesseqgtr N^S$.

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[88] This is because, when p is lower (higher) than $1/N$, the higher probability raises the prospect that a firm will earn π^M in a market (other firms enter a market so that a firm will earn nothing there).

[89] This is verified in the proof of proposition 6-1.

[90] If Δ is negative at γ_1 *and* γ is larger than and close to γ_{Π_1}, p^S is still closer to $1/N$ than p^I is. Here, larger net profits (in the *I* regime) are *solely* due to smaller aggregate investment (not larger gross profits). The same applies to (d) if Δ is negative at γ_2 *and* γ is smaller than and close to γ_{Π_2}.

[91] Here, I implicitly assumed that N was a continuous variable solely to simplify the analysis.

(b) If $p^I > 1/N^I \ \forall\gamma$ *and* $\gamma \lessgtr (1-\theta)/\theta$, *then* $N^I \gtrless N^S$.

(c) If $\exists\ \gamma_1 (\in(0,(1-\theta)/\theta))$ *s.t., at* γ_1, *both* $\alpha = 0$ *and* Δ *is positive or negative but close to 0,* $N^I = N^S$ *if* $\gamma = (1-\theta)/\theta$ *or* $\gamma = \gamma_{\Pi_1}$; $N^I > N^S$ *if* $\gamma \in (\gamma_{\Pi_1}, (1-\theta)/\theta)$; $N^I < N^S$ *otherwise.*

(d) If $\exists\ \gamma_2 (\in((1-\theta)/\theta, 1))$ *s.t., at* γ_2, *both* $\alpha = 0$ *and* Δ *is positive or negative but close to 0,* $N^I = N^S$ *if* $\gamma = (1-\theta)/\theta$ *or* $\gamma = \gamma_{\Pi_2}$; $N^I > N^S$ *if* $\gamma \in ((1-\theta)/\theta), \gamma_{\Pi_2})$; $N^I < N^S$ *otherwise.*

Combining the results obtained so far, I can characterise the nature of the organization which will facilitate more entry.

In case (a), the organisation that induces the *more competitive* R&D at N^I and has the *more efficient* assimilative process induces more entry. The more competitive R&D under one organization (at N^I) yields the larger amount of information per project, e. Moreover, when γ is small (large), this type of organisation, Separated (Integrated) R&D, can assimilate information more efficiently due to specialisation (much cross fertilisation). Thus, it produces an even higher probability. As higher probability enhances profitability here, I get the above outcome.

In case (b), the organization which induces *more competitive* R&D at N^I and has a *less efficien*t assimilative process promotes more entry. The effect of competitive R&D is the same as in case (a). However, when γ is small (large), such an organization, Integrated (Separated) R&D, has a less efficient assimilative process due to small cross fertilization and the size effect (no cross fertilization) Thus, it

generates a lower probability though more input is used there. However, here the lower probability is *beneficial* to firms as it prevents (gross) profits from being dissipated, which eventually leads to the above outcome. [92]

I can now advance a conjecture on whether total expansion of contractual R&D in the biotechnology industry will lead to more concentration at the R&D stage. The success probability for R&D and the assumption that $\gamma < (1-\theta)/\theta$ are the same as in Chapter 4. Moreover, I will consider the case where more than 10 large firms engage in R&D for each product, which is likely to cover most cases in the industry. Finally, in order to examine the impact of total expansion of contractual R&D, I will compare the outcome of the *I* regime with that of the *S* regime as in Chapter 5.

Thus, I conjecture that, if R&D is for standard products, the expansion will result in *more* concentration. As $1/N < 1/10 < 0.53 \approx p^I$, (b) or (c) in corollary 6-1 is quite likely to apply to this case where γ is close to $(1-\theta)/\theta$. Here the probability is *too high* relative to the number of firms involved in R&D. I showed that in-house R&D would induce more entry due to their *inefficient* assimilative process.

On the contrary, if R&D is for novel products, the expansion will lead to *less* concentration. For, usually, not so many (definitely not nearly 80) firms are involved in R&D of novel products. Thus, it is likely that $1/N > 0.0125 = 1/80 \approx p^I$ so that (a) or (d) in corollary 6-1 are quite likely to apply to this case. In this case, the probability is *too low*. Thus, contractual R&D would induce more entry due to its more *efficient* assimilative process than In-house R&D.

However, the recent development of pharmacogenomics and combinatorial

[92] Using a similar argument, it is easy to figure out case (c) and (d).

chemistry would alter this assessment in the future. [93] They are said to improve cost effectiveness of drug development (and, quite probably, many biological products). This will lower $x'(e)$ for all e, which induces units to set the larger e and, thus, raises the success probability. Thus, R&D for new products will be better approximated by (d) or, even, (b) in corollary 6-1. This means that the expansion of contractual R&D could lead to *more* concentration whether R&D is for novel or standard products.

5. Welfare comparison.

This section compares social welfare under each regime. Again, the outcome turns out to depend on the relationship between the probability p^I and $1/N^I$. If p^I is small relative to $1/N^I$, the organization which yields the higher probability generates the larger welfare. For it can not only produce the larger welfare given any N but also induce more entry than the other organization. However, if p^I is large relative to $1/N^I$, the one which yields the *lower* probability generates the larger welfare. For, though it generates the smaller welfare given any N than the other, it enhances more entry, which raises welfare.

The latter result is similar to the one in Motta (1992). In his case, when industry structure and the spillover rate are the same in both non-cooperative R&D and RJVs, the former induces more R&D investment than the latter and, thus, is likely to result in the larger welfare if the spillover rate is small. However, if the spillover rate is between 1/11 and 1/3, only two firms can viably operate in non-cooperative

[93] See The Economist (1998) for pharmacogenomics and combinatorial chemistry.

R&D while in RJVs more than 3 firms. Because more firms can operate in RJVs, market competition is more fierce and, thus, welfare is in the end larger there. The difference between his case and ours is that in his case additional entry is due to coordination in RJVs so as to make positive profits if more than 3 firms operate. In our case, it is due to the inefficient R&D process, which enhances profits by preventing the expected gross profits from being dissipated.

I also advance a conjecture on whether total expansion of contractual R&D will lead to larger welfare. Unlike in the previous two chapters, I take into account the impact of the expansion on industry structure. Then I show that, depending on the nature of R&D, the expansion has ambiguous effects on welfare and that the current developments in biotechnology can have an adverse effect on welfare.

The rest of the section shows these results in detail.

Let ω^M and ω^O be social welfare in market k under monopoly and oligopoly respectively where $\omega^O > \omega^M$. Defining $W^r(N)$ as net expected welfare in regime r when N firms operate, I write social welfare in the I regime and the S regime as

$$W^I(N) = 2\left\{Np^I(1 \quad p^I)^{N-1}\omega^M + \left[1-(1-p^I)^N - Np^I(1-p^I)^{N-1}\right]\omega^O - Nx\right\} - Ng. \qquad (6\text{-}8)$$

$$W^S(N) = 2\left\{Np^S(1-p^S)^{N-1}\omega^M + \left[1-(1-p^S)^N - Np^S(1-p^S)^{N-1}\right]\omega^O - Nx\right\} - Ng. \qquad (6\text{-}9)$$

For later reference, consider the special case where $N^I = N^S$.

Proposition 6-2. $W^I(N) \gtreqless W^S(N) \ \forall N$ *if* $\gamma \gtreqless (1-\theta)/\theta$.

Figure 6-4

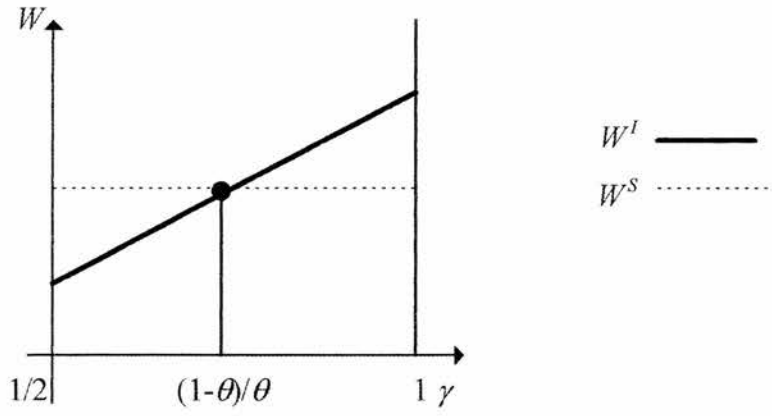

Figure 6-4 depicts this result. It says that if the number of firms is the same under the two regimes, Separated R&D is socially better than Integrated R&D iff γ is small, and *vice versa*. The organization which produces the higher probability generates larger gross welfare by producing the high probability of Bertrand competition in a market. This will lead to larger net welfare there as well.

In order to get some definite results, I make the following plausible assumptions.

Assumption 2. (i) $\omega^O - \omega^M$ is large; (ii) $d(1-p^r)^N / dN < 0 \ \forall N, r$;

(iii) $W^{r'}(N^{r'}) > W^r(N^r) > W^{r'}(N^r)$ if $N^{r'} > N^r$ where $r \neq r'$.

(ii) says that the more units engage in project k the less likely it is that all fail in it. This and (i) ensure that there occurs socially *insufficient* entry in both regimes. [94] (iii) uses this fact and simplifies the analysis. It says that, when welfare is smaller in

[94] See Appendix 6-B.

regime r' than in regime r at N^r, further entry in regime r' will reverse this. [95]

Corollary 6-2. Define $\Delta = |p^I - (1/N^I)| - |p^S - (1/N^I)|$ *and suppose that Assumption 2 hold.*

(a) If $p^I < 1/N^I$ $\forall\gamma$ *and* $\gamma \gtreqless (1-\theta)/\theta$, *then* $W^I(N^I) \gtreqless W^S(N^S)$.

(b) If $p^I > 1/N^I$ $\forall\gamma$ *and* $\gamma \gtreqless (1-\theta)/\theta$, *then* $W^I(N^I) \lesseqgtr W^S(N^S)$.

(c) If $\exists\ \gamma_1 \in (0,(1-\theta)/\theta)$ *s.t., at* γ_1, *both* $\alpha = 0$ *and* Δ *is either positive or negative but close to 0, then* $W^I(N^I) = W^S(N^S)$ *if* $\gamma = (1-\theta)/\theta$; $W^I(N^I) > W^S(N^S)$ *if* $\gamma \in (\gamma_{\Pi_1}, (1-\theta)/\theta)$; $W^I(N^I) < W^S(N^S)$ *otherwise.*

(d) If $\exists\ \gamma_2 \in ((1-\theta)/\theta, 1)$ *s.t., at* γ_2, *both* $\alpha = 0$ *and* Δ *is either positive or negative but close to 0, then* $W^I(N^I) = W^S(N^S)$ *if* $\gamma = (1-\theta)/\theta$; $W^I(N^I) > W^S(N^S)$ *if* $\gamma \in ((1-\theta)/\theta, \gamma_{\Pi_2}]$; $W^I(N^I) < W^S(N^S)$ *otherwise.*

As in corollary 6-1, I can summarize the nature of the organization which generates the larger welfare in each case.

In case (a) where p^I is relatively small, the organization which has the *more efficient* assimilative process produces a socially *more efficient* market outcome. Proposition 6-2 says that, at N^I, the organization with such R&D process generates the larger welfare. *Moreover*, such organization facilitates more entry, which is socially desirable due to insufficient entry under both regimes.

[95] I assume that the first inequality in (iii) holds, which is quite likely unless N^r is very large.

In case (b) where p^I is relatively high, the organization which has the *less efficient* assimilative process generates a socially *more efficient* market outcome. In this case, for one organization to yield the *larger welfare* than the other, it would indeed *need some inefficiency* in R&D process. Proposition 6-2 says that the inefficient process yields the smaller welfare than the efficient one at N^I. However, corollary 6-1 indicates that the former induces more entry, which makes Integrated R&D more socially desirable in this respect. If assumption 2(iii) holds, the effect of industry structure dominates that of the more efficient R&D process. Thus, the organization with the inefficient R&D process could produce the larger welfare. [96]

The conjecture on whether the expansion of contractual R&D will result in larger welfare is as follows. If R&D is for novel products, the expansion is likely to result in the larger welfare than if all firms used in-house R&D instead. For, as $1/N > 0.0125 \approx p^I$, (a) or (d) in corollary 6-2 are quite likely to apply to this case. However, if R&D is for standard products, the expansion will lead to smaller welfare. As $1/N < 1/10 < 0.53 \approx p^I$, (b) or (c) in corollary 6-2 is likely to apply to this case where γ is close to $(1-\theta)/\theta$. Moreover, arguments in corollary 6-1 imply that, with development of pharmacogenomics and combinatorial chemistry, R&D for new products will become better approximated by (b) or (c) of corollary 6-2. As a result, the expansion will result in smaller welfare even for novel products.

[96] Case (c) and (d) can be worked out by using the above arguments.

6. Extension

I have so far confined the analysis to two symmetric cases and compared them in order to examine the impact of *total* expansion of contractual R&D on industry structure and welfare. Here, I will briefly analyze the case where *some* firms use Separated R&D, which I call the Hybrid (*H*) regime. Then I will compare the *I* regime with the *H* regime to examine the impact of *partial* expansion of contractual R&D on industry structure and welfare.

Now suppose that N-n firms use Integrated R&D and the remaining n firms use Separated R&D where $1 \le n \le N$-1. If firm i uses Integrated R&D and firm f delegates project b to lab f, I can write their payoffs respectively as

$$\Pi_i = \left[p_{ia}(1-p_{i'a})^{N-n-1}(1-p_{fa})^n + p_{ib}(1-p_{i'b})^{N-n-1}(1-p_{fb})^n\right]\pi^M - x(e_{ia}) - x(e_{ib}) \quad \forall i \neq i' \quad (6\text{-}10)$$

$$\Pi_{fa} = p_{fa}(1-p_{ia})^{N-n}(1-p_{fa})^{n-1}\pi^M - x(e_{fa}) + F_H \qquad \forall f \neq f' \quad (6\text{-}11)$$

$$\Pi_{fb} = p_{fb}(1-p_{ib})^{N-n}(1-p_{fb})^{n-1}\pi^M - x(e_{fb}) - F_H \qquad \forall f \neq f' \quad (6\text{-}12)$$

respectively. p_{ik} and $p_{i'k}$ are given by (6-1) while p_{fk} and $p_{f'k}$ by (6-2). I assume, for simplicity, that F_H is exogenous and solves $\Pi_{fb} = 0$ in equilibrium. In what follows, superscripts *IH* and *SH* refer to an equilibrium under Integrated R&D and Separated R&D in the *H* regime respectively.

Proposition 6-3. Suppose that $1-(N-n)p^{IH} > 0 \ \forall\gamma$. *Then,* $\Pi^{IH} > (\le)\Pi^{SH}$ *if* $\gamma < (\ge)\ (1-\theta)/\theta$ *and* γ *is close to* $(1-\theta)/\theta$. *Equality holds only if* $\gamma = (1-\theta)/\theta$.

Tedious calculations show that Separated (Integrated) R&D always produces the higher probability if γ is smaller (larger) than and close to $(1-\theta)/\theta$. This surely means larger gross profits there, which eventually results in larger net profits. [97]

Let N^H be the number of firms that can earn non-negative profits in the H regime.

Corollary 6-3. If $1 - Np^I > 0 \ \forall\gamma$, $1-(N-n)p^{IH} > 0 \ \ \forall\gamma$, $N^H \leq N^I(N^S) \leq N^S(N^I)$ *if* γ *is smaller (larger) than and close to* $(1-\theta)/\theta$. *All equalities hold iff* $\gamma = (1-\theta)/\theta$.

That is, if the success probability is low both in the I regime and the H regime, the H regime results in less entry than in the symmetric regimes. Take a small γ case for instance and suppose that N^r firms plan to run R&D in the H regime where $r = I, S$. In the H regime, a unit under Integrated R&D has a lower information assimilation ability than under Separated R&D. This dampens the incentive for the unit under Integrated R&D to set a larger e for two reasons. First, given an arbitrary e by all units, the probability of success is smaller for the unit under Integrated R&D than under Separated R&D. Second, the higher probability of the unit under Separated R&D means that the expected payoff from successful R&D for the unit under Integrated R&D , $(1-p_i)^{N^r-n-1}(1-p_f)^n\pi^M$ is smaller than that for the unit under Separated R&D, $(1-p_i)^{N^r-n}(1-p_f)^{n-1}\pi^M$. The smaller e of the unit under

[97] Proposition 6-3 considers the case where a success probability is relatively low. However, the result may hold even when it is relatively high. For, in the H regime the probability is *always* higher

Integrated R&D leads to the small profits. This makes it impossible for the firm under Integrated R&D to earn profits large enough to cover the entry cost g unless some firms under Integrated R&D stays out.

This result implies that if R&D is for novel products so that the probability is low, partial expansion of contractual R&D will result in *more* concentration at the R&D stage. However, total expansion will result in *less concentration.* [98]

Corollary 6-4. If $1 - Np^I > 0 \ \forall\gamma$, $1-(N-n)p^I > 0 \ \ \forall\gamma$, *and* γ *is smaller (larger) than and close to* $(1-\theta)/\theta$, $W^S(N^S)\left(W^I(N^I)\right) \geq W^I(N^I)\left(W^S(N^S)\right) \geq W^H(N^H)$ *where equalities hold only if* $\gamma = (1-\theta)/\theta$.

This says that welfare is always the smallest in the H regime. The reason is as follows. For instance, when $\gamma < (1-\theta)/\theta$ and an arbitrary N is given, the I regime is the less socially efficient industry configuration than the H regime in that it generates smaller welfare. [99] However, corollary 6-3 says that the I regime induces more entry, which has a desirable effect on welfare, which eventually makes welfare larger in the I regime. The S regime yields the larger welfare than the H regime not only because it is the socially more efficient configuration at an

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under Separated (Integrated) R&D at $\gamma < (>) (1-\theta)/\theta$ and, thus, gross profits are *always* larger there.

[98] If R&D is for standard products so that the probability is high, then it is possible from fn. 96 and proposition 6-1 (b) that $N^H < N^S < N^I$ is possible if γ is smaller than and close to $(1-\theta)/\theta$. That is, partial expansion will lead to the same outcome as above. However, here, total expansion too leads to *more* concentration.

[99] See Appendix 6-C.

arbitrary N [100] but also because it induces more entry.

The welfare implication of the expansion of contractual R&D is obvious. If R&D is for novel products so that the probability is low, partial expansion will result in the smaller welfare whereas total expansion will lead to larger welfare. [101]

7. Conclusion.

I analyzed whether Separated R&D would lead to less concentration at the R&D stage than Integrated R&D and the effect of the resultant industry structure on welfare. The outcome depends on the success probability and the number of firms involved in R&D as well as on some exogenous factors. Using as a first approximation plausible estimates of the crucial variables in the biotechnology industry, I reached the conclusion that it makes a difference whether contractual R&D is deployed for *standard or novel* products. Moreover, in view of recent developments which *routinise* biotechnological R&D, the current enthusiasm for contractual R&D is likely to be misplaced.

This chapter used a highly simplified model for analysis, and one may question robustness of the results, e.g. what happens to the results if I remove a Bertrand competition assumption and restore spillovers across units. It is not possible to say something definite, but some conjectures are possible. Note that there is an analogy

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[100] See Appendix 6-C.

[101] If a remark in fn. 92 holds, $W^I(N^I) > W^S(N^S) > W^H(N^H)$ if the probability is high, and γ is smaller than and close to $(1-\theta)/\theta$. This means that if R&D is for standard products so that the probability is high, partial expansion will lead to the same outcome as above. However, here, even if expansion is total, it results in smaller welfare.

between (a) in corollary 6-1 and proposition 4-1, and (b) in the corollary and proposition 4-2. For, the former results consider the case where the probability is relatively low and the intuition there is quite similar. If the essence of the results in Chapter 4 holds for a N firm case, which I believe is quite likely, much of (a) and (b) in corollary 6-1 and, subsequently, in corollary 6-2 will remain valid even if I relax some assumptions as above. [102]

[102] How such a change in the assumption will alter (c) and (d) in both corollaries is not clear.

Appendix A.

Proof of lemma 6-1. Evaluating (6-6) at $e = e^S$ and using (6-7), I get

$$\partial \Pi^I / \partial e \big|_{e=e^S} = \left(\pi^M \sum_{h=1}^{N-1} \delta^{N-h-1} \varepsilon^{h-1} \right) \left((\theta(1+\gamma))^{\frac{1}{N-1}} - 1 \right) \left(1 - e^S \sum_{h=1}^{N} \left((\theta(1+\gamma))^{\frac{1}{N-1}} \right)^{N-h} \right)$$

where $\delta = (1-\theta(1+\gamma)e^S)(\theta(1+\gamma))^{\frac{1}{N-1}} > 0$, $\varepsilon = 1 - e^S > 0$. [103] Defining

$\alpha = 1 - e^S \sum_{h=1}^{N} \left((\theta(1+\gamma))^{\frac{1}{N-1}} \right)^{N-h}$, I prove the lemma. Q.E.D.

Proof of Lemma 6-2. Applying implicit the function theorem to (6-6), we get

$$de^I / d\gamma = [\pi^M \theta (1 - p^I)^{N-2} (1 - N p^I)] / D. \qquad \text{(A.6-1)}$$

$$dp^I / d\gamma = \theta e^I + \theta(1+\gamma)(de^I / d\gamma) = \theta [e^I x'' + \theta(1+\gamma)\pi^M (1-p^I)^{N-1}] / D > 0 \ \forall \gamma. \qquad \text{(A.6-2)}$$

where $D = x''(e^I) + \pi^M (\theta(1+\gamma))^2 (N-1)(1-p^I)^{N-2} > 0$. (A.6-2) and that

$p^I = p^S$ if $\gamma = (1-\theta)/\theta$ imply lemma 6-2. Q.E.D.

Proof of proposition 6-1. Note from (6-6) and (6-7) that $\Pi^I = \Pi^S$ if $\gamma = (1-\theta)/\theta$.

Totally differentiating (6-3) w.r.t. e^I and γ, I get

[103] As $\theta(1+\gamma)e^S$ is the probability of a project in the *I* regime and is assumed not to exceed 1, $\delta > 0$.

$$\frac{d\Pi^I}{d\gamma} = \underbrace{\left(\frac{2\pi^M \theta e^I x''(e^I)(1-p^I)^{N-2}}{D}\right)}_{+}(1-Np^I) \Rightarrow sign\left(\frac{d\Pi^I}{d\gamma}\right) = sign\left(1-Np^I\right). \quad \text{(A.6-3)}$$

Thus, if $1-Np^I > (<)0 \ \forall\gamma$ and $\gamma \gtreqless (1-\theta)/\theta$, $\Pi^I \lesseqgtr (\gtreqless)\Pi^S$. This proves (a) and (b).

To prove (c), suppose that γ_1 exists. Since $e^I = e^S$ at $\gamma = (1-\theta)/\theta$ and $\gamma = \gamma_1$, and $d(1-Np^I)/d\gamma < 0 \ \forall\gamma$ from (A.6-2), I can find from (A.6-1) that there exists a unique $\gamma^* (\in (\gamma_1, (1-\theta)/\theta))$ such that $1-Np^I = 0$ at $\gamma = \gamma^*$ and $1-Np^I > (<)0$ if $\gamma < (>)\gamma^*$. This and lemma 6-1 imply that $p^S > 1/N > p^I$ at γ_1. Note that

$$d[\pi^M p(1-p)^{N-1}]/dp$$
$$= \pi^M [(1-p)^{N-1} - (N-1)p(1-p)^{N-2}] = \pi^M (1-p)^{N-2}(1-Np). \quad \text{(A.6-4)}$$

Let $\Delta = |p^I - (1/N)| - |p^S - (1/N)|$. (A.6-4) and that $p^S > 1/N > p^I$ at γ_1 say that, if Δ is non-negative at γ_1, the gross profits are no smaller in the S regime than in the I regime and, thus $\Pi^I \leq \Pi^S$ at γ_1. As $1-Np^I = 0$ at $\gamma = \gamma^*$ and $\Pi^I = \Pi^S$ at $\gamma = (1-\theta)/\theta$, this and (A.6-3) imply that there exists a unique $\gamma_{\Pi_1} (\in (0, (1-\theta)/\theta))$ such that $\Pi^I = \Pi^S$ at $\gamma = \gamma_{\Pi_1}$. If Δ is negative but close to 0 at γ_1, then $\Pi^I > \Pi^S$ but the difference is small. Thus, $\Pi^I = \Pi^S$ at some γ close to and smaller than γ_1, which means that γ_{Π_1} exists in this case. Finally, as Π^I has a global maximum at $\gamma = \gamma^*$, that $\Pi^I = \Pi^S$ at $\gamma = (1-\theta)/\theta$ and at $\gamma = \gamma_{\Pi_1}$ implies (c).

The proof of (d) is similar. Suppose that γ_2 exists. Following the similar argument as above, I can verify that if Δ is positive or negative but close to 0 at γ_2,

then $\Pi^I = \Pi^S$ at γclose to γ_2. Defining γ which yields $\Pi^I = \Pi^S$ at $\gamma > (1\text{-}\theta)/\theta$ as γ_{Π_2} and using the fact that Π^I has a global maximum at $\gamma^{**} \in ((1-\theta)/\theta), \gamma_2)$, I prove (d). Q.E.D.

Proof of corollary 6-1. If I assume free entry equilibrium, then proposition 6-1 immediately leads to corollary 1. Q.E.D.

Proof of proposition 6-2. Totally differentiating (6-8) w.r.t. e^I and γ,I get

$$\frac{dW^I}{d\gamma} = 2N\left[\underbrace{(1-p^I)^{N-2}}_{+}\left(\underbrace{\Delta\omega}_{-}\underbrace{(1-Np^I)}_{?}+\underbrace{\omega^O(1-p^I)}_{+}\right)\underbrace{\left(\frac{dp^I}{d\gamma}\right)}_{+}-\underbrace{x'}_{+}\underbrace{\left(\frac{de^I}{d\gamma}\right)}_{?}\right]. \quad \text{(A.6-5)}$$

where $\Delta\omega = \omega^M - \omega^O < 0$. If $1-Np^I \le 0$, $de^I/d\gamma \le 0$ from (A.6-1) so that the sign of (A.6-5) is positive. Moreover, using (6-6) and rearranging (A.6-5), I get

$$\frac{dW^I}{d\gamma} = \underbrace{\frac{2\theta N(1-p^I)^{N-2}}{D}}_{+}\left[\underbrace{\omega e^I x''}_{?}+\underbrace{\theta(1+\gamma)\pi^M(1-p^I)^{N-1}}_{+}\underbrace{\left(\omega-(1-Np^I)\pi^M\right)}_{?}\right]. \quad \text{(A.6-6)}$$

where $\omega = \omega^M(1-Np^I)+\omega^O(N-1)p^I$. If $1-Np^I > 0$, then $\omega > 0$ and

$$\omega-(1-Np^I)\pi^M = \omega^O(N-1)p^I+(1-Np^I)(\omega^M-\pi^M) > 0 \quad (\because \omega^M > \pi^M).$$

Thus, the sign of (A.6-6) is positive.

With an arbitrary N in both regimes, obviously $W^I = W^S$ at $\gamma = (1-\theta)/\theta$. Combining this with the result on (A.6-5) and (A.6-6), I prove the proposition. Q.E.D.

Proof of corollary 6-2. Since entry is socially insufficient in both regimes, $W^{r'}(N^{r'}) > W^{r'}(N^r) > W^r(N^r)$ if $N^{r'} > N^r$ where $r \neq r'$. Using this, corollary 6-1, proposition 6-2, assumption 2(iii), I can easily prove corollary 6-2. Q.E.D.

Proof of proposition 6-3. From (10) and (11), FOCs are

$$\partial \Pi^{IH} / \partial e = \theta(1+\gamma)(1-p^{IH})^{N-n-1}(1-p^{SH})^n \pi^M - x'(e^{IH}) = 0 \qquad \text{(A.6-7)}$$

$$\partial \Pi^{SH} / \partial e = (1-p^{IH})^{N-n}(1-p^{SH})^{n-1} \pi^M - x'(e^{SH}) = 0. \qquad \text{(A.6-8)}$$

Suppose that $1-(N-n)p^{IH} > 0 \ \forall \gamma$. Now let an arbitrary γ go up infinitesimally. Given e^{IH} and e^{SH}, that makes (A.6-8) negative. Then units under Separated R&D lower e^{SH} to, say, e^{SH_1} to make (A.6-8) equal to 0. On the contrary, a larger γ raises $\theta(1+\gamma)$ in (A.6-7) but lowers $(1-p^{IH})^{N-n-1}$ there. If $1-(N-n)p^{IH} > 0 \ \forall \gamma$, the former outweighs the latter so that (A.6-7) becomes positive.[104] This and the lower e^{SH} induce firms using Integrated R&D to raise e^{IH} to, say, e^{IH_1} to make (A.6-7)

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[104] Note that when e^{IH} *and* e^{SH} *are given* and $1-(N-n)p^{IH} > 0 \ \forall \gamma$,

$$\partial \theta(1+\gamma)(1-p^{IH})^{N-n-1}(1-p^{SH})^n \pi^M / \partial \gamma = \theta \pi^M (1-p^{IH})^{N-n-2}(1-p^{SH})^n (1-(N-n)p^{IH}) > 0.$$

This implies that in the circumstance marginal revenues (cost) in (A.6-7) go up (remains unchanged) with a larger γ, which makes (A.6-7) positive.

equal to 0. This causes e^{SH_1} to go down to e^{SH_2} as an optimal response, which raises e^{IH_1} to e^{IH_2} to make (A.6-7) equal to 0 as before. This iterative process continues so

$$\ldots\ldots\ldots e^{SH_2} < e^{SH_1} < e^{SH} \text{ and } e^{IH} < e^{IH_1} < e^{IH_2} \ldots\ldots\ldots$$

The series generated by this process is monotonic. Moreover, as e is closed and bounded by definition, the series converges. That is, $e^{IH^*}(> e^{IH})$ and $e^{SH^*}(< e^{SH})$, which are the limit of these series, make (A.6-7) and (A.6-8) hold. As e^{IH} and e^{SH} are continuous in γ and the two inequalities are based on an arbitrary γ, $de^{IH}/d\gamma > 0 > de^{SH}/d\gamma \ \forall\gamma$. [105] Totally differentiating (A.6-7) and (A.6-8) w.r.t. e^{IH}, e^{SH} and γ, and using Cramer's Rule, I get

$$\begin{pmatrix} de^{IH}/d\gamma \\ de^{SH}/d\gamma \end{pmatrix} = \frac{1}{|H|}\begin{pmatrix} \lambda_{22} & -\lambda_{12} \\ -\lambda_{21} & \lambda_{11} \end{pmatrix}\begin{pmatrix} \theta\pi^M(1-p^{IH})^{N-n-2}(1-p^{SH})^n(1-(N-n)p^{IH}) \\ -\theta\pi^M e^{IH}(N-n)(1-p^{IH})^{N-n-1}(1-p^{SH})^{n-1} \end{pmatrix}$$

$$\Rightarrow \begin{pmatrix} + \\ - \end{pmatrix} = \frac{1}{|H|}\begin{pmatrix} + & - \\ - & + \end{pmatrix}\begin{pmatrix} + \\ - \end{pmatrix} \Rightarrow |H| > 0 \forall\gamma \text{ if } 1-(N-n)p^{IH} > 0 \ \forall\gamma. \qquad \text{(A.6-9)}$$

where $|H| = \lambda_{11}\lambda_{22} - \lambda_{12}\lambda_{21}$

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[105] I can verify from (A.6-9) that $dp^{IH}/d\gamma = \theta e^{IH} + \theta(1+\gamma)(de^{IH}/d\gamma) > 0 > dp^{SH}/d\gamma \equiv de^{SH}/d\gamma$ if γ is close to $(1-\theta)/\theta$ and $|H|>0 \ \forall\gamma$. This and the obvious fact that $p^{IH} = p^{SH}$ at $\gamma = (1-\theta)/\theta$ imply that $p^{IH} > (<) p^{SH}$ if γ is larger (smaller) than and close to $(1-\theta)/\theta$ and $|H|>0 \ \forall\gamma$.

$$\lambda_{11} = \pi^M(\theta(1+\gamma))^2(N-n-1)(1-p^{IH})^{N-n-2}(1-p^{SH})^n + x''(e^{IH}) > 0$$

$$\lambda_{12} = \theta(1+\gamma)\pi^M n(1-p^{IH})^{N-n-1}(1-p^{SH})^{n-1} > 0$$

$$\lambda_{21} = \theta(1+\gamma)\pi^M(N-n)(1-p^{IH})^{N-n-1}(1-p^{SH})^{n-1} > 0$$

$$\lambda_{22} = \pi^M(n-1)(1-p^{IH})^{N-n}(1-p^{SH})^{n-2} + x''(e^{SH}) > 0$$

Totally differentiating Π^{IH} and Π^{SH} w.r.t. e^{IH}, e^{SH} and γ, and applying the envelope theorem, I get $d\Pi^{IH}/d\gamma$ and $d\Pi^{SH}/d\gamma$. Evaluating them at $\gamma = (1-\theta)/\theta$, using (A.6-8), $dp^{IH}/d\gamma = \theta e^{IH} + \theta(1+\gamma)(de^{IH}/d\gamma)$ and $dp^{SH}/d\gamma \equiv de^{SH}/d\gamma$, I get

$$\left.\frac{d\Pi^{IH}}{d\gamma}\right|_{\gamma=\frac{1-\theta}{\theta}} = \frac{2\theta\pi^M x''e^*(1-e^*)^{N-2}}{|H|}\left[\left(1-(N-n)e^*\right)x'' + (N-n)(1-e^*)^{N-n-1}\pi^M\right] > 0. \quad \text{(A.6-10)}$$

$$\left.\frac{d\Pi^{SH}}{d\gamma}\right|_{\gamma=\frac{1-\theta}{\theta}} = \frac{-2\theta\pi^M x''e^*(1-e^*)^{N-2}(N-n)}{|H|}\left[e^*x'' + (1-e^*)^{N-1}\pi^M\right] < 0. \quad \text{(A.6-11)}$$

where e^* is the equilibrium amount of information of a project at $\gamma = (1-\theta)/\theta$.

If $\gamma = (1-\theta)/\theta$, then (A.6-7) and (A.6-8) correspond so that $\Pi^{IH} = \Pi^{SH}$. This, (A.6-10) and (A.6-11) imply the proposition. Q.E.D.

Proof of corollary 6-3. Note that (6-6), (6-7), (A.6-7), and (A.6-8) are identical at $\gamma = (1-\theta)/\theta$ so that $\Pi^{SH} = \Pi^S = \Pi^I = \Pi^{IH}$, i.e. $N^H = N^I = N^S$ at $\gamma = (1-\theta)/\theta$.

If $1 - Np^I > 0$ and $1-(N-n)p^{IH} > 0 \ \forall\gamma$, (A.6-3) and (A.6-10) are positive. Note

$$d(\Pi^{I}-\Pi^{IH})/d\gamma\big|_{\gamma=(1-\theta)/\theta}=\underbrace{\left(-2\theta\pi^{M}x''e^{*}(1-e^{*})^{N-2}/|H|\right)}_{-}\Big\{\underbrace{ne^{*}x''}_{+}$$

$$+\underbrace{\left[(N-n)+(1-Ne^{*})(1-e^{*})^{n-1}\right](1-e^{*})^{N-n-1}\pi^{M}}_{+}\Big\}<0. \quad \text{(A.6-12)}$$

Thus, (A.6-11), (A.6-12), corollary 6-1(a), and the result at $\gamma=(1-\theta)/\theta$ imply that $\Pi^{SH}>\Pi^{S}>\Pi^{I}>\Pi^{IH}$ if $1-Np^{I}>0$, $1-(N-n)p^{IH}>0\ \forall\gamma$, and γ is smaller than and close to $(1-\theta)/\theta$. This means that if $1-Np^{I}>0$, $1-(N-n)p^{IH}>0\ \forall\gamma$, and γ is smaller than and close to $(1-\theta)/\theta$,

$\Pi^{SH}-g>\Pi^{S}-g>\Pi^{I}-g=0>\Pi^{IH}-g$ at $N=N^{I}$, i.e., $N^{H}<N^{I}<N^{S}$.

Using a similar argument, I can easily verify that

$N^{H}<N^{S}<N^{I}$ if $1-Np^{I}>0$, $1-(N-n)p^{IH}>0\ \forall\gamma$, and γ is larger than and close to $(1-\theta)/\theta$. Q.E.D.

Proof of corollary 6-4. Obvious from corollary 6-3 and assumption 2-(iii). Q.E.D.

Appendix 6-B.

Differentiating (6-9) w.r.t. N, I get

$$\frac{dW^{I}(N)}{dN}=2\left[(\omega^{M}-\omega^{O})\frac{d(Np^{I}(1-p^{I})^{N-1})}{dN}-\omega^{O}\frac{d(1-p^{I})^{N}}{dN}-Nx'\frac{de^{I}}{dN}\right]-(2x+g). \quad \text{(B.6-1)}$$

where $\frac{d(Np^I(1-p^I)^{N-1})}{dN} = p^I(1-p^I)^{N-1} + N(1-p^I)^{N-1}\frac{dp^I}{dN} + Np^I\frac{d(1-p^I)^{N-1}}{dN}$. (B.6-2)

Since $\Pi^I = 2p^I(1-p^I)^{N^I-1}\pi^M - 2x - g = 0$ at $N = N^I$,

$$\frac{dW^I(N^I)}{dN} = 2\left[\underbrace{\Delta\omega}_{-}\underbrace{\left(N^I(1-p^I)^{N^I-1}\frac{dp^I}{dN} + N^I p^I\frac{d(1-p^I)^{N^I-1}}{dN}\right)}_{?}\right.$$

$$\left. - \omega^O\underbrace{\left(p^I(1-p^I)^{N^I-1} + \frac{d(1-p^I)^{N^I}}{dN}\right)}_{?} + \underbrace{(\omega^M - \pi^M)p^I(1-p^I)^{N^I-1}}_{+} - \underbrace{N^I x'\frac{de^I}{dN}}_{?}\right]. \quad \text{(B.6-3)}$$

where $de^I/dN = \{\pi^{MO}\theta(1+\gamma)(1-p^I)^{N^I-1}\log(1-p^I)\}/D < 0 \quad (\because \log(1-p^I) < 0)$, (B.6-4)

$$dp^I/dN = \{\pi^{MO}(\theta(1+\gamma))^2(1-p^I)^{N^I-1}\log(1-p^I)\}/D < 0 \quad \text{(B.6-5)}$$

$$\begin{aligned} d(1-p^I)^{N-1}/dN &= (1-p^I)^{N-1}\{\log(1-p^I) - [(N-1)/(1-p^I)](dp^I/dN)\} \\ &= [(1-p^I)^{N-1}x''\log(1-p^I)]/D < 0 \end{aligned}. \quad \text{(B.6-6)}$$

Thus, if $p^I(1-p^I)^{N^I-1} + d(1-p^I)^{N^I}/dN \le 0$, (B.6-3) is positive.

Now consider the case where $p^I(1-p^I)^{N^I-1} + d(1-p^I)^{N^I}/dN > 0$. Using the fact that $dp^I/dN = \theta(1+\gamma)(de^I/dN)$ and rearranging (B.6-3), I get

$$\frac{dW^I(N^I)}{dN} = 2\left[\underbrace{\Delta\omega}_{-}\underbrace{\frac{d(N^I p^I(1-p^I)^{N^I-1})}{dN}}_{?} - \underbrace{\omega^O\frac{d(1-p^I)^{N^I}}{dN}}_{-} - \pi^M\underbrace{\left(N^I\frac{dp^I}{dN} + p^I\right)}_{?}\right]. \quad \text{(B.6-7)}$$

I consider two cases where $p^I + N^I(dp^I/dN) > 0$ and $p^I + N^I(dp^I/dN) \le 0$.

First suppose that $p^I + N^I(dp^I/dN) > 0$. Since

$$d(1-p^I)^N/dN = (1-p^I)^N\{\log(1-p^I) - [N/(1-p^I)](dp^I/dN)\}, \quad \text{(B.6-8)}$$

by using this, (B.6-2) and (B.6-8) and approximating $\log(1-p^I)$ with $-p^I$, I get

$$\frac{dW^I(N^I)}{dN} > 2\left[\Delta\omega\frac{d(N^I p^I(1-p^I)^{N^I-1})}{dN} - \omega^O\frac{d(1-p^I)^{N^I}}{dN} - \omega^M\left(N^I\frac{dp^I}{dN} + p^I\right)\right]$$

$$= 2(1-p^I)^{N^I-1}\left\{\omega^M N^I p^I\frac{d(1-p^I)^{N^I-1}}{dN} - \omega^O\left[\frac{d(N^I p^I(1-p^I)^{N^I-1})}{dN} + \frac{d(1-p^I)^{N^I}}{dN}\right]\right\}$$

$$\approx 2(1-p^I)^{N^I-1}\left\{-\omega^M p^I N^I\underbrace{\left[p^I + \frac{N^I-1}{1-p^I}\frac{dp^I}{dN}\right]}_{?} + \omega^O p^I(N^I-1)\underbrace{\left[p^I + \frac{N^I}{1-p^I}\frac{dp^I}{dN}\right]}_{?}\right\}. \quad \text{(B.6-9)}$$

Using the approximation, $\log(1-p^I) \approx -p^I$, and substituting that into (B.6-6), I get

$$\frac{d(1-p^I)^{N-1}}{dN} \approx (1-p^I)^{N-1}\left\{-p^I - \frac{N-1}{1-p^I}\frac{dp^I}{dN}\right\} < 0 \Rightarrow p^I + \frac{N-1}{1-p^I}\frac{dp^I}{dN} > 0. \quad \text{(B.6-10)}$$

Besides, using the assumption that $d(1-p^I)^{N-1}/dN < 0 \ \forall N$,

$$d(1-p^I)^N / dN = (1-p^I)^N[x'' - \pi^M(\theta(1+\gamma))^2(1-p^I)^{N-2}]\log(1-p^I)/D < 0$$

$$\Rightarrow x'' - \pi^M(\theta(1+\gamma))^2(1-p^I)^{N-2} > 0$$

$$\Rightarrow p^I + [N^I/(1-p^I)](dp^I/dN) \approx p^I(x'' - \pi^M(\theta(1+\gamma))^2(1-p^I)^{N-2}) > 0 . \text{(B.6-11)}$$

Note that

$$\underbrace{p^I(N^I-1)\left[p^I + \frac{N^I}{1-p^I}\frac{dp^I}{dN}\right]}_{v_1} - \underbrace{p^I N^I\left[p^I + \frac{N^I-1}{1-p^I}\frac{dp^I}{dN}\right]}_{v_2} = -(p^I)^2 < 0 . \qquad \text{(B.6-12)}$$

(B.6-12) says that the difference between v_1 and v_2 is small while I assumed that $\omega^O - \omega^M$ is reasonably large. Thus, (B.6-9) and, thus, (B.6-7) will be positive.

Next suppose that $p^I + N^I(dp^I/dN) \le 0$. If so, then

$$\frac{d(Np^I(1-p^I)^{N-1})}{dN} = (1-p^I)^{N-1}\left(p^I + N\frac{dp^I}{dN}\right) + Np^I\frac{d(1-p^I)^{N-1}}{dN} < 0$$

Thus, (B.6-7) is positive in this case.

Appendix 6-C.

Social welfare in the *H* regime is written as

$$W^H(N) = 2\left\{p^M\omega^M + p^O\omega^O - (N-n)x(e^{IH}) - nx(e^{SH})\right\} . \qquad \text{(C.6-1)}$$

where $p^M = (1-p^{IH})^{N-n-1}(1-p^{SH})^{n-1}\left[(N-n)p^{IH}(1-p^{SH}) + np^{SH}(1-p^{IH})\right]$,

$$p^O = 1 - p^M - (1 - p^{SH})^n (1 - p^{IH})^{N-n}.$$

As (6-6), (6-7), (A.6-7), and (A.6-8) are identical $\gamma = (1-\theta)/\theta$, it is obvious that $W^I(N) = W^S(N) = W^H(N)\ \forall N$ at $\gamma = (1-\theta)/\theta$.

Differentiating (C.6-1) w.r.t. γ, I get

$$\frac{dW^H(N)}{d\gamma} = 2\Big\{\Big\{(N-n)(1-p^{SH})\Big[(1-p^{SH})(1-(N-n)p^{IH}) - np^{SH}(1-p^{IH})\Big]\frac{dp^{IH}}{d\gamma}$$

$$+ n(1-p^{IH})\Big[(1-p^{IH})(1-np^{SH}) - (N-n)p^{IH}(1-p^{SH})\Big]\frac{dp^{SH}}{d\gamma}\Big\}$$

$$*(1-p^{IH})^{N-n-2}(1-p^{SH})^{n-2}(\omega^M - \omega^O) + \omega^O(1-p^{IH})^{N-n-1}(1-p^{SH})^{n-1}$$

$$*\left[(N-n)(1-p^{SH})\frac{dp^{IH}}{d\gamma} + n(1-p^{IH})\frac{dp^{SH}}{d\gamma}\right] - (N-n)x'(e^{IH})\frac{de^{IH}}{d\gamma} - nx'(e^{SH})\frac{de^{SH}}{d\gamma}\Big\}. \quad \text{(C.6-2)}$$

Evaluating (C.6-2) at $\gamma = (1-\theta)/\theta$ and using (A.6-7), (A.6-8), (A.6-9), and fn.104, I get

$$\left.\frac{dW^H(N)}{d\gamma}\right|_{\gamma=\frac{1-\theta}{\theta}} = 2(1-e^*)^{N-2}\left\{\left[(N-n)\frac{de^{IH}}{d\gamma} + n\frac{de^{SH}}{d\gamma}\right]\right.$$

$$\left.*\left[\omega^* - (1-e^*)\pi^M\right] + \theta e^*(N-n)\omega^*\right\} \quad \text{(C.6-3)}$$

where $\omega^* = (1-Ne^*)(\omega^M - \omega^O) + (1-e^*)\omega^O$ and

$$(N-1)\frac{de^{IH}}{d\gamma}\bigg|_{\gamma=\frac{1-\theta}{\theta}}+\frac{de^{SH}}{d\gamma}\bigg|_{\gamma=\frac{1-\theta}{\theta}}=\frac{\theta\pi^{M}(N-n)(1-Ne^{*})(1-e^{*})^{N-2}}{x''+\pi^{M}(N-1)(1-e^{*})^{N-2}}. \quad \text{(C.6-4)}$$

Substituting (C.6-4) into (C.6-3), I get

$$\frac{dW^{H}(N)}{d\gamma}\bigg|_{\gamma=\frac{1-\theta}{\theta}}=\frac{2\theta(N-n)(1-e^{*})^{N-2}}{D}\Big\{e^{*}x''\omega^{*}$$

$$+\pi^{M}(1-e^{*})^{N-1}\left[\omega^{*}-(1-Ne^{*})\pi^{M}\right]\Big\} \quad \text{(C.6-5)}$$

Evaluating (A.6-6) at $\gamma=(1-\theta)/\theta$, I get

$$\frac{dW^{H}(N)}{d\gamma}\bigg|_{\gamma=\frac{1-\theta}{\theta}}=\frac{N-n}{N}\frac{dW^{I}(N)}{d\gamma}\bigg|_{\gamma=\frac{1-\theta}{\theta}}>0. \quad \text{(C.6-6)}$$

This means that $W^{I}(N)\left(W^{S}(N)\right)>W^{H}(N)>W^{S}(N)\left(W^{I}(N)\right)\ \forall N$

if $\gamma>(<)\ (1-\theta)/\theta$ and γ is close to $(1-\theta)/\theta$.

Chapter 7. Conclusion

In the last three chapters, I examined profitability, social welfare, and industry structure under in-house R&D and contractual R&D. In spite of some differences in the models in each chapter, I found some robust results.

Chapters 4 and 6 considered the case where all firms use in-house R&D, which I called the Integrated (I) regime and the case where all use contractual R&D, which I called the Separated (S) regime. Table 1 summarizes the result. First, consider the case where industry structure is the same in both regimes and that the success probability of a project is relatively low in the I regime. Then profits are larger in the S regime than in the I regime if the cross fertilization rate is small and/or the size effect is substantial. On the other hand, if the success probability is relatively high, profits are larger in the I regime than in the S regime if the cross fertilization rate is small and/or the size effect is large.

Chapter 5 examined whether, given the R&D organization of its rival firm, a firm can earn larger profits with in-house R&D or contractual R&D. If the rate of cross fertilization is small and/or the size effect is large, profits are larger if a firm uses contractual R&D. Otherwise the result is reversed.

The implications for social welfare are as follows. Assuming that industry structure is the same in the I regime, the S regime, and the H regime where one firm uses in-house R&D and the other contractual R&D, welfare was the largest in the S regime if the cross fertilization rate is small and/or the size effect is severe. Otherwise, the I regime generates the largest welfare. The H regime always yields the second largest welfare.

Table 1 Comparison of profits in two regimes. [106]

	A low p^I case	A high p^I case
A large size effect (small θ) and/or little cross fertilization (small γ)	$\Pi^I < \Pi^S$	$\Pi^I > \Pi^S$
A small size effect (large θ) and/or much cross fertilization (large γ)	$\Pi^I > \Pi^S$	$\Pi^I < \Pi^S$

Table 2 Comparison of industry structure in two regimes in free entry equilibrium. [107]

	A low p^I case	A high p^I case
A large size effect (small θ) and/or little cross fertilization (small γ)	$N^I < N^S$	$N^I > N^S$
A small size effect (large θ) and/or much cross fertilization (large γ)	$N^I > N^S$	$N^I < N^S$

Table 3 Comparison of social welfare in two regimes in free entry equilibrium

	A low p^I case	A high p^I case
A large size effect (small θ) and/or little cross fertilization (small γ)	$W^I(N^I) < W^S(N^S)$	$W^I(N^I) > W^S(N^S)$
A small size effect (large θ) and/or much cross fertilization (large γ)	$W^I(N^I) > W^S(N^S)$	$W^I(N^I) < W^S(N^S)$

Chapter 6 also examined whether the S regime will induce more entry of firms than the *I* regime. Table 2 summarizes the result. Using the above result on profitability, I found that if the success probability of a project was low in the *I*

[106] All notations in this table are specified in Chapter 4.

[107] All notations in Tables 2 and 3 are specified in Chapter 6.

regime, the *S* regime would promote more entry than in the *I* regime if the cross fertilization rate is small and/or the size effect is severe. Conversely, if the above success probability is high, the *I* regime will facilitate more entry than in the *S* regime if the cross fertilization rate is small or the size effect is severe.

The result of welfare comparisons is altered if I take into account the impact of industry structure on welfare. Table 3 summarizes the result. If the success probability in the *I* regime is low, welfare is larger in the *S* regime than in the *I* regime if the cross fertilization rate is small and/or the size effect is severe. If the probability is high, welfare is larger in the *I* regime than in the *S* regime if the rate is small or the size effect is severe.

Using these results, I made a conjecture on the impact of the expansion of contractual R&D in the biotechnology industry on profitability, social welfare, and industry structure. The *I* regime was regarded as the case where there was no expansion while the *S* (*H*) regime as the one where there was *total* (*partial*) expansion. Thus, in order to examine the impact of the expansion on market outcomes, I applied some reasonable estimates derived in the empirical literature on industrial biotechnology to the above results and examined whether profitability and social welfare are larger in the *S* (*H*) regime than in the *I* regime.

A conjecture on profitability is summarized in Tables 4 and 5. The key factor is the degree of competition in final good markets. If market competition is of the less competitive Cournot type, partial expansion will lead to the larger (smaller) profits for firms under contractual (in-house) R&D if the cross-unit spillover rate is small. However, if the rate is non-trivial, the expansion will lead to increase in profits for *all* firms. Total expansion will result in larger profits.

Table 4 The impact of expansion of contractual R&D on profits when final good markets are less competitive. [108]

	Partial expansion	Total expansion
A small cross unit spillover rate	smaller (larger) profits for a firm under in-house (contractual) R&D $(\Pi^{PI} < \Pi^{N} < \Pi^{PC})$	larger profits for all firms $(\Pi^{N} < \Pi^{T})$
A non-trivial cross unit spillover rate	larger profits for all firms $(\Pi^{N} < \Pi^{PC}, \Pi^{N} < \Pi^{PI})$	larger profits for all firms $(\Pi^{N} < \Pi^{T})$

Table 5 The impact of expansion of contractual R&D on profits when final good markets are very competitive.

	Partial expansion	Total expansion
R&D for novel products	smaller (larger) profits for a firm under in-house (contractual) R&D $(\Pi^{PI} < \Pi^{N} < \Pi^{PC})$	larger profits for all firms $(\Pi^{N} < \Pi^{T})$
R&D for standard products	smaller (larger) profits for a firm under in-house (contractual) R&D $(\Pi^{PI} < \Pi^{N} < \Pi^{PC})$	smaller profits for all firms $(\Pi^{N} > \Pi^{T})$

If market competition is of the very fierce Bertrand type, it becomes important whether R&D is for novel or products or standard ones. When R&D is aimed at novel products, partial expansion will lead to larger (smaller) profits for firms under contractual (in-house) R&D regardless of the cross unit spillover rate. Total expansion will result in the same outcome as in the Cournot case. When R&D is

[108] In Tables 4 and 5 Π^{N} and Π^{T} are profits for a firm in the No expansion case and in the Total expansion case respectively while Π^{PI} (Π^{PC}) is profits for a firm under in-house (contractual) R&D in the Partial expansion case.

Table 6 The impact of expansion of contractual R&D on industry structure. [109]

	Partial expansion	Total expansion
R&D for novel products	more concentration $(N^N > N^P)$	less concentration $(N^N < N^T)$
R&D for standard products	more concentration $(N^N > N^P)$	more concentration $(N^N > N^T)$

Table 7 The impact of expansion of contractual R&D on social welfare when industry structure is taken into account. [110]

	Partial expansion	Total expansion
R&D for novel products	smaller welfare $(W^N > W^P)$	larger welfare $(W^N < W^T)$
R&D for standard products	smaller welfare $(W^N > W^P)$	smaller welfare $(W^N > W^T)$

aimed at standard products, the outcome of partial expansion will be the same as in a novel product case. However, total expansion will lead to smaller profits for all firms. This is due to the fact that the success probability is too *high* if firms use contractual R&D. Thus in the end too many firms are likely to enter the final good market. Together with fierce market competition, this will dissipate the expected profits of firms. The expansion will generate a Prisoner's Dilemma outcome.

A conjecture predicts that the expansion, whether partial or total, will result in larger welfare. Moreover, it will occur regardless of the degree of competition in a final good market and whether R&D is aimed at novel or standard products.

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[109] N^N, N^P, and N^T are the number of firms which can *viably* conduct R&D in the No expansion case, in the Partial expansion case, and in the Total expansion case respectively.

[110] W^N, W^P, and W^T are social welfare in the No expansion case, in the Partial expansion case, and in the Total expansion case respectively.

Table 6 summarizes a conjecture on industry structure *at the R&D stage*. Partial expansion results in more concentration regardless of the nature of R&D. However, if I examine the impact of total expansion on industry structure, the distinction in the nature of R&D plays a key role. If R&D is for novel products, total expansion will result in *less concentration* while if R&D is for standard products, the expansion will lead to *more* concentration.

The above conjecture on welfare did not take into account industry structure. If it is incorporated, a different outcome emerges, which is summarized in Table 7. Partial expansion will lead to the *smaller* welfare. For, the expansion will lead to more concentration, whose adverse effect on welfare is non-trivial. If R&D is for standard products, total expansion will lead to *smaller* welfare for the same reason as above. However, if R&D is for novel products, the expansion will lead to *larger* welfare. It is not only because the expansion results in less concentration but also because firms will run R&D with contractual R&D (that is more productive in output (i.e. success probability) generation than in-house R&D).

Finally, there have been two recent developments in biotechnology, combinatorial chemistry and pharmacogenomics. These are said to make R&D for pharmaceutical and, more broadly, any biotechnology-related research easier. This means that R&D units will achieve a higher success probability than now. Suppose that the current trend of the expansion of contractual R&D continues, which is quite likely according to The Economist (1998). Then, together with these developments, the expansion, whether partial or total, will result in fewer firms engaged in R&D in each biotechnology-related industry and, hence, smaller welfare. From this viewpoint, the current emphasis on contractual R&D is likely to be misplaced.

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