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ABSTRACT

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The first essay examines how the shift between single-tasking and multitasking influences productivity and workers' bargaining power, and its implications on the distribution of earnings between management and workers. Under single-tasking, a firm can obtain high productivity because workers' hold-up power can provide them with larger incentives to work. In contrast, a firm that uses multitasking reduces workers' hold-up power by making them substitutable, but the firm may lose productivity. This paper shows that a worker with specialized skills will earn a higher wage in single-tasking and that one with general skills will earn a higher wage in multitasking. Moreover, a shift by a firm from single-tasking to multitasking can widen the earnings gap between management and workers. Lastly this paper shows that the organization of production mediates the effect of technological change on relative earnings.

The second essay examines the effect of control rights on decision to publish or patent research results. University researchers have substantial discretion over disclosure, while managers in non-academic organizations often direct researchers to patent their findings. Thus, the effect of control rights can be identified by using the shift from basic to commercializable knowledge because a manager has a greater incentive to protect the commercializable

knowledge. The effect, however, may be confounded by the heterogeneity of research projects. To overcome this issue, this paper exploits multiple discoveries associated with a single human gene as a research path and a discovery of a gene's linkage to a disease that may spark commercially oriented research on that gene. Building on this variation of knowledge along research paths, the differences-in-differences estimate shows that over time, non-academic research organizations become less likely to publish and more likely to patent than universities.

The third essay examines how the make-or-buy decision on corporate R&D is related to different types of innovations. The key trade-off in this decision is between time savings in the research stage and adaptation cost in the production stage. Specifically, the adaptation cost relative to the value of the product and the number of distinct goods to which the technology is applied will influence this trade-off. If the relative adaptation cost is high, and a technology is applied to a broad range of goods, a firm is likely to develop such technology in-house and the rate of innovation will be slower; if technology will generate a narrow range of goods, a firm tends to obtain the technology from the marketplace and the innovation rate will be rapid.

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CHAPTER 1

Introduction

This dissertation discusses how organizational design impacts production, rent distribution and technology selection to analyze the source of heterogeneity in economic outcomes. In economics, these issues are typically analyzed as an equilibrium of individual economic agents' behaviors in the marketplace. However, the marketplace also consists of various organizations that regulate their members' incentives and behaviors. For production to occur, the agents' labor, capital and technological knowledge need coordination and allocation to the production process within organizations. At the same time, the organization can also distribute individuals' compensation with the "visible hand." How will the "visible hand" generate heterogeneous outcomes in the production of tangible and intangible goods and the distribution of gains thereof between members?

Recent developments in organizational economics allow us to specify what aspects of organization can influence production and distribution among agents. This dissertation focuses on the structure of organization as a key factor: First, the structure can fundamentally differentiate incentives of agents inside and outside an organization. Agents inside an organization will have different incentives from agents outside the organization because the structure of an organization requires agents to adapt themselves to the structure as long as they want to stay inside. Second, if organizations have a similar structure, agents in those organizations may show similar behavioral patterns on average. Lastly, the structure is fixed in the short term but variable in the long term. Thus, we may test empirical implications of organizational design on incentives and behaviors of agents. Therefore, this paper theoretically and empirically examines how structural aspects of organization – specifically, flexible task assignment, distribution of decision rights and the boundary of the firm – influences incentives and decision making of individuals inside an organization in regard to productivity, earnings distribution, knowledge generation and innovation. Thus, this dissertation consists of three essays.

The first essay examines how the shift from single-tasking to multitasking affects productivity and the bargaining power of workers. Based on this analysis, this essay explores the implication of flexible task assignment in regard to the distribution of earnings between management and workers and predicts the possible impact of technological change that reduces the cost of multitasking on the relative earnings. First, the shift to multitasking will reduce workers' bargaining power because they can perform their colleagues' tasks and become substitutable. This weakened bargaining power will reduce workers' incentives to invest in their tasks. The ultimate effect of flexible task assignment on productivity will depend on whether the workers are good at multitasking. Second, if the workers are not good at multitasking, the shift to multitasking will reduce their pay because they will earn a smaller portion of a smaller sized revenue. In this case, the earnings gap between management and workers will widen. Lastly, if technological change reduces the fixed cost of multitasking, it widens the relative earnings between management and workers through the adoption of multitasking.

This study contributes to the literature in the several ways. First, it introduces the mode of production as a factor influencing the distribution of earnings between management and workers. To analyze this effect of production method, this study stresses the bargaining aspect of multitasking. Second, it provides a microeconomic model of a "rent-splitting parameter" between management and workers based on tasks assignment and intra-firm bargaining. Lastly, it can suggest a window on the source of inter-industry wage differentials because workers with the same skill can get compensated differently depending on the chosen production method.

The second essay quantifies the impact of management on the disclosure of knowledge by scientists. To do so, this study examines how scientists in academic and non-academic institutions differentially disclose their findings in publications and patent on human gene research. Academic institutions give researchers the liberty of how to disclose scientific findings. In contrast, non-academic institutions such as firms and government labs usually give their management the right to decide how to disclose researchers' findings. By exploiting this institutional difference, this study shows that scientists in and out of academia respond differently to the same "shock" that can spark commercializable research. Specifically, this study regards multiple discoveries associated with a single human gene as a research path. Then, an identifiable shift from the basic to the commercialization stage occurs when a gene is discovered to be disease-related. This discovery can spark commercially oriented research on that gene. To identify the effect of management, a difference-in-difference analysis before and after the discovery across academic and non-academic institutions is implemented. This study finds that compared to university scientists, non-academic scientists tend to publish the commercializable discovery less and patent it more. For example, researchers in biotech publish

50-percent less than university researchers in the commercialization stage. More surprisingly, researchers at non-academic public institutions such as government labs are 2.4 times as likely to patent as university researchers during the commercialization stage.

This study makes several contributions. First, it suggests an effective control variable to address the unobserved heterogeneity of science projects by constructing a measurable research path -- multiple discoveries from a single gene. Second, it suggests a way of identifying basic and commercializable stages in each research path by using a discovery that can spark commercially oriented research. Lastly, this paper demonstrates that the management of research, rather than profit motivation, could affect scientists' decisions to disclose the information. In particular, scientists at government labs and other non-academic research organizations may protect commercializable findings more aggressively under the direction of the management.

The third essay examines why firms shift between developing a necessary technology in-house and purchasing a new technology in the market, and how this make-or-buy decision on technology can be related to different types of innovations and innovation rates. The key trade-off in this decision is time savings in the research stage and the adaptation cost in the production stage. If a firm develops a new technology in-house, it may incur a longer development time on average, but it could save adaptation cost in the subsequent production stage because it would be easier to transfer the knowledge in-house. In contrast, if a firm obtains a new technology from the marketplace, the time saving in the research stage could be offset by a higher adaptation cost in the production stage. This make-or-buy decision will depend on the adaptation cost relative to the value of product and the number of distinct goods to which the technology is applied. If the relative adaptation cost is high, and a technology is applied to a broad range of goods, a firm is likely to develop such technology in-house and the rate of innovation will be slower. If technology is applied to a narrow rage of goods, a firm tends to obtain the technology from the marketplace and the innovation rate will be rapid. In addition, a firm is more likely to obtain a new technology from the marketplace if the adaptation cost decreases, the value of goods increases and research costs increase. The decision regarding the source of new technology development involves considering the subsequent adaptation cost in the production stage. As a result, the decision of where to produce a new technology is related to the types of innovations. Lastly, this study suggests that we can expect rapid but narrow-range technological change if in-house R&D labs give more weight to their role as monitors of external technological advances rather than producers of a new technology.

CHAPTER 2

How does the division of labor affect the distribution of earnings? Implications of the organization of production

2.1. Introduction

Earnings differentials have widened substantially in the last two decades, creating a dramatic gap between those at the top of the distribution and those at the bottom, with gaps all along the way. According to Dew-Becker and Gordon (2005), despite the stable labor's share of total income from 1966 to 2001, only the top 10 percent of the income distribution enjoyed gains in productivity growth. Especially, the ratio of CEOs' compensation to average worker's compensation increased from 27 in 1973 to 237 in 2001 (Dew-Becker and Gordon 2005). The wage gap also grew between skilled workers and unskilled workers even though the relative supply of skilled workers in terms of education had increased (Hornstein, Krusell and Violante 2005; Katz and Autor 1999). At the same time, researchers reported that workers with similar education and experience earned different wages across industries even if they performed jobs of similar difficulties (Katz and Summers 1989).

Economists have tried to explain the above perplexing but important phenomena by using mainly the "supply-demand-institution" approach (Katz and Autor 1999). This approach highlights shifters of the relative demand for skilled labor such as immigration, international trade and technological change, and institutional factors such as the decline of unionization. Explanations based on these factors have provided insights on the growing dispersion of earnings distribution. The literature based on the supply-demand-institution approach, however, has not examined firms' organizational factors in detail, even though firms are major employers and their human resource management is known to influence employees' wages and other company benefits.

Recently, there has been a surge in research that examines earnings inequality by combining organizational factors and relative demand for skilled workers. This research shows that firms' environmental changes, such as technological progress, increase the relative demand for skilled workers because firms' responses to this progress favor more skilled workers (Acemoglu 1999; Bresnahan, Brynjolfsson and Hitt 2002; Garicano and Rossi-Hansberg 2006; Thesmar and Thoenig 2000). These researchers assume that skill differences among economic players already exist in explaining how technology and organizations widen earnings differentials. In addition, they mainly examine the organizational change that requires only highly skilled workers to work with advanced technology. However, they do not seem to provide a good explanation of the wage differential across industries between workers with the same skill. The researchers do not consider the cost of bargaining either, which is intrinsic in an organization. Does the organization of a firm influence the wage determination? How does a firm generate earnings differentials between management and workers in a non-union setting? How does technological change influence the distribution of earnings when workers' skills remain constant?

This paper argues that the division of labor within a firm can influence the distribution of earnings even when workers have the same skill. Specifically, this paper examines how a firm's decision to enhance the flexibility of labor use can reduce the productivity of workers and their share of the gains. A firm chooses to have a worker perform either one specific task or multiple tasks when tasks are complementary to produce a good, and the firm hires multiple workers. Absent bargaining power issue, multitasking is socially optimal because it allows multiple workers to efficiently allocate their productive efforts. However, the production method can influence the bargaining power of workers relative to management because the chosen method changes the interdependence among workers performing complementary tasks. Moreover, if bargaining power affects workers' incentives to produce, production method can simultaneously affect the size and division of productivity gains.

With regard to the selection of the degree of specialization, however, a firm faces a trade-off between the amount of productive investment it can elicit and the bargaining power over production under a given method. By adopting single-tasking, the firm allows workers to have more bargaining power because the firm's substitution of a worker can negatively impact other workers' productivity and the whole production ("bottleneck externality"). When a firm uses single-tasking in team production, the unexpected absence of a worker can cause a bottleneck in production, because the other workers' investment on the complementary tasks becomes less productive. However, the firm can elicit more investment from each worker because workers' marginal costs will decrease and workers will have strong bargaining power over the productivity gains. The adoption of multitasking can eliminate the bottleneck externality because individual workers take charge of a whole set of complementary tasks; however, the firm may reduce the amount of productive investment from workers when workers split their investment over multiple tasks and have weak bargaining power over the productivity gains. The equilibrium will depend on the skill composition (specific vs. general) of a worker.

This paper demonstrates that workers with the same skills can be differently compensated depending on which production method the company adopts: Specialists earn higher wages in single-tasking and generalists earn higher wages in multitasking. This paper also shows that under some conditions, the adoption of multitasking is likely to widen the earning differentials between management and workers because it reduces the bargaining power of workers more than it increases productive efficiency. And the effect of technological progress on the earnings gap between management and workers depends on whether workers' skill compositions match the type of technological progress: If workers are specialists, multitasking-biased technological progress always widens the gap. If they are generalists, technological progress can narrow the gap.

This study contributes to current literature in the following ways: First, by examining the shift of bargaining power as well as incentives in multitasking, this paper suggests that a production method can be a factor that affects the evolution of earnings distribution. Second, this paper provides a microeconomic model of "rent-splitting parameter" between management and workers. Third, this paper shows a mechanism through which internal organization mediates the effect of technological change on relative earnings. The right combination of workers' skills and the division of labor can affect the distribution of earnings within a firm. Lastly, this study suggests that production method can be an explanation of inter-industry wage differentials.

Workers with the same skill sets can have different compensation depending on industries' production methods.

This paper is organized as follows: Sections 2.2 and 2.3 examine literature review and motivating examples. Sections 2.4 and 2.5 develop a formal model of the division of labor and its implications on the distribution of earnings. Sections 2.6 and 2.7 discuss the robustness and extensions of this model, such as the effect of the external labor market. Section 2.8 is a conclusion.

2.2. Productivity, Bargaining and Organization in the Determination of Earnings

Since Adam Smith, economists have examined the determination of earnings in terms of the tension between the roles of competitive factors and those of institutional factors. Researchers have focused on compensating wage differential, human capital and labor market institutions, such as minimum wage and unions. Although scholars have agreed that the division of labor influences the productivity of workers, they mainly explore how the market size restricts the degree of specialization and leads to an increase in productivity.

It has been agreed, however, that earnings depend on the productivity of workers, and that not much attention has been paid to whether the division of labor can influence the earnings structure of workers. To examine this question, we need to look inside a firm, because it is a firm that directly decides the degree of specialization and wages after considering work conditions, human capital and technology. Skill-biased technological change literature in the supply-demand-institution (SDI) approach and efficiency wage literature have been the two main strands that examine the role of the firm in the wage structure.

Skill-biased technological change literature incorporates a firm's decision into the supply-demand-institution paradigm to examine the evolution of wage structure. The literature assumes that different skill groups are imperfect substitutes in production and that shift in relative demand due to skill-biased technological change alter wage structure (Katz and Autor 1999). Another important assumption is that the effect of skill-biased technological change on wage structure depends on differences in wage-setting institutions. Based on that assumption, researchers examine a firm's response to environmental change. Factors that influence a firm's response are diverse: information and learning (Lindbeck and Snower 2000); hierarchical structure in knowledge (Garicano and Rossi-Hansberg 2006); technological choice with a fixed cost and product market volatility (Thesmar and Thoenig 2000); change in the job composition; and relative supply of skilled workers (Acemoglu 1999).

The studies, however, focus on how the internal decisions of a firm propagate already existing skill differences between workers. As studies on the "inter-industry wage differential" suggest (Dickens and Katz 1986, Krueger and Summers 1988), workers with the same skills may earn different wages depending on their industry. Skill-biased technological change literature also assumes that skill and technological progress has a unilateral relationship: Technological progress means more complicated technology and therefore higher skills. However, the level of skills that technological progress requires can be different (Goldin and Katz 1996): Producing technology needs higher skill as this literature assumes. Using technology, however, does not necessarily require higher skills because technology becomes easier to end-users. And most workers are the users rather than the producers of technology. Thus, technological progress favoring skilled workers requires in-depth examination.

Efficiency wage literature focuses on firms' strategic initiatives rather than the competitive market force in wage determination. (Shapiro and Stiglitz 1984). Studies demonstrate that information and incentive issues inside a firm can raise wages above market equilibrium. This theory is effective in explaining wage differentials between workers with the same skills, which skill-biased technological change literature does not actively examine. Empirical literature based on the efficiency wage theory also focuses on inter-industry wage differentials (Groshen 1991; Dickens and Katz 1986; Katz and Summers 1989; Krueger and Summers 1988).

The efficiency wage theory, however, cannot coherently explain the long-term pattern of the evolution of earnings differentials such as the U-shaped relative earnings trajectory in the 20th century without introducing a long-term decision of a firm. If productivity can restrain wages, and organizational factors such as the degree of specialization can influence the productivity of workers, there is a possibility that a long-term strategic decision other than a compensation scheme for incentive can influence the evolution of wage structure.

Recently, there has been literature on how the hold-up problem by workers influences the wage determination of a firm in incomplete contract settings. In their paper, Stole and Zwiebel (1996 a, b) show that a firm incurs over-employment to reduce the hold-up power of workers. In their analyses, workers can hold up because they are not replaceable in the short run. Through ex-ante over-employment and the maintenance of an "internal labor pool," a firm can reduce workers' bargained wages to their reservation wages (Stole and Zwiebel 2003). de Fontaney and Gans (2003) show that a firm can also incur under-employment if a finite external pool of replacement workers exists. Still, these studies do not examine the possibility that an initial production structure can affect ex-ante workers' incentive of investment in their tasks.

Developing the property rights approach (Hart and Moore 1990), Rajan and Zingales (1998) model that the control of access to assets can regulate hold-up problems when the relationship-specific investments on tasks are the source of hold-up power of workers. The equilibrium number of access depends on how production technology aggregates workers' investment. In equilibrium, one worker should be granted access to one machine if the technology is additive, and that one worker should have access to all machines if the technology is either substitute or complementary. However, Rajan and Zingales do not consider that granting access can also change workers' marginal cost of investment in tasks.[1] If a worker has a set of specific and general skills, the scope of his task can affect his marginal costs and eventually the productivity of a firm.

Therefore, the task of this paper is to examine the determination of earnings structure in terms of the trade-off between productivity and bargaining over production and to show how the choice of the production method inside a firm can influence the trade-off and generate the current patterns of earnings differentials. In the subsequent section, historical studies suggest that the division of labor can be one of the driving forces in the determination of workers' compensation and the distribution of earnings.

[1] For example, Henry Ford insisted that "The average worker…wants a job in which he does not have to think," when he designed the mass production system (Rubenstein 2001). Conversely, the critics of lean production system point out that the system is too demanding for workers. They term it "management by stress" (Babson 1995; Slaughter 1990).

2.3. Flexible Use of Labor and Productivity: Ford and NUMMI

Recent literature implies that the introduction of flexibility in the workplace has a puzzling effect on workers. Osterman (1994, 2000) nationally surveyed private-sector establishments with 50 or more employees to examine the diffusion of high-performance work organization (HPWO) practices such as teamwork and job rotation and its effect on the relative gains of workers. He confirmed that firms adopted these HPWO practices at a rapid rate and that workers seemed to like the broad scope of their jobs and the opportunity to share ideas. He concluded, however, that the adoption of HPWO practices was associated with (a) significantly increased layoff rates in subsequent years in non-union establishments and (b) no compensation gains to workers. Specifically, Osterman found that the layoff did not necessarily mean that employment shrank at those establishments (Osterman 1999, 2000). How can workers prefer HPWO practices even if these practices allow workers compensation that is disproportionate to productivity gains?

Two examples illustrate how the flexible use of labor inside a firm can influence productivity and workers' compensation: (a) Ford's mass production system and the "five-dollar" day episode (Raff 1987; Raff and Summers 1986) and (b) team production system by New United Motors Manufacturing, Inc. (Adler 1993; Brown and Reich 1989; Slaughter 1990). Each case demonstrates how the shift between single-tasking and multitasking influences productivity, the type of major work burden and workers' compensation.

The Ford Motor Company case shows that the rigid specialization can improve workers' compensation proportionate to productivity gains. The company started its business by employing skilled craftsmen with "broad discretion in the direction of their own work and that of their helpers" (Raff and Summers 1986). When Ford decided to produce only Model T's in 1908, however, the company changed its production method: Tasks were divided more and more finely and became more and more routinized. Unskilled workers carried out those tasks with single-purpose tools and the assembly line. By 1913, output had risen twenty-five-fold over the preceding five years. The introduction of a new production method fundamentally changed the work life of production workers: The pace of the assembly line made them feel pressured to work faster (Raff and Summers 1986).

On January 4, 1914, Henry Ford suddenly announced a wage raise for workers in his plants from two dollar to five dollar per day ("five-dollar day"). According to Raff (1988), the out-of-pocket cost of the raise was estimated to be $10 million in one year. At that time, the total profits were forecast at only $20 million (Raff 1988). Raff examines alternative explanations to Ford's motivation and concludes that the excess demand for workers, information and incentive to monitor cannot explain Ford's wage policy satisfactorily (Raff 1988).

Raff notes that the five-dollar wage was possible because of Ford's mass production system and suggests that the "rent-sharing" explanation is the most plausible. He maintains that "more intensive use of fixed and quasi-fixed factors through smooth coordination of work flows… was the real source of the profits" (Raff and Summers 1986).

Other firms in the auto industry followed Ford's wage initiative only after they adopted Ford's mass production system. By 1928, even before the UAW became important, the average wage in the automobile industry was 40 percent higher than in other manufacturing industries (Raff and Summers 1986).

The case of New United Motors Manufacturing, Inc. (NUMMI) illustrates how the introduction of a flexible production method increases productivity disproportionate to workers' compensation (Adler 1993; Brown and Reich 1989). The company, a joint venture between General Motors (GM) and Toyota, began operation in Fremont, California, in 1984. NUMMI took over the facilities of the GM-Fremont plant that GM permanently closed in 1982 and introduced the "Toyota way" of plant operations, such as team concept and multi-skilling workers. Eighty-five percent of the workers that NUMMI hired were former employees of the GM-Fremont plant. The United Auto Workers (UAW) continued to present them and maintained its hierarchy in the new plant (Adler 1993).

Although the GM-Fremont plant had the worst in productivity, quality and labor strife in the GM system, the new plant had become the most productive auto assembly plant in the United States within two years (Alder 1993). For example, compared to the GM-Fremont plan, the labor productivity of hourly waged workers at NUMMI increased by 49 percent and absenteeism decreased from 20-25 percent to 3-4 percent.

Workers' compensation at NUMMI was set at a level similar to the one at GM-Fremont because the company followed the national UAW contract. However, workers at NUMMI worked harder than they did at GM-Fremont. According to Alder (1993), experienced workers worked a hypothetical 57 seconds out of 60 seconds at NUMMI, whereas at GM-Fremont they had worked approximately 45 seconds out of 60 seconds.

Teamwork succeeded in either reducing absenteeism through peer pressure or reducing the costs of absenteeism because it reduced the disruption of production by using multi-skilling workers (Adler 1993). Although almost all workers seemed to prefer the NUMMI way of working to the one at GM-Fremont, some workers were concerned that the weakened union at NUMMI might not protect them anymore. Thus, there has been a debate on whether the introduction of teamwork on the work floor actually was “management by stress” (Slaughter 1990).

These two cases imply that production method influences the efficient allocation of workers’ efforts as well as their bargaining power over production through internal substitution between workers. Therefore, the shift between single-tasking and multitasking can affect the size and division of productivity gains. The following section formalizes this economics of production method.

2.4. Model

This paper assumes that a firm consists of one manager and two workers, and that it faces a unit demand for its product. This paper also assumes that the manager already has hired the workers and that they share symmetric information. Finally, the lack of an external labor market prevents the manager from hiring a new worker during production.[2]

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[2] We can alternatively interpret the lack of the external labor market in terms of task-specific human capital investment. If performing tasks requires workers to make machine-specific investments before production occurs, a manager of the firm will perceive that there is no external labor market just before production begins.

Players and Task-specific Knowledge. A manager and two identical workers produce a good to sell in the market. The production of the good requires tasks A and B; each task needs a machine and labor. Production requires skill, knowledge of how to work on specific tasks and physical labor. This paper abstracts physical labor from production – as long as workers have skills and knowledge of how to work, workers will supply inelastic physical labor. Both workers already possess the skills required to perform both tasks, but they need to make task-specific human capital investments (e.g., searching for and learning information on how to perform a task well) before production occurs. Workers incur costs to develop their private "best practices" for a given task. However, such knowledge of the best practice for a specific task can be less valuable or useless for the other task (Gibbons and Waldman 2004). This paper assumes that a best practice for task A has no value for task B and that workers need to make separate investments to develop their best practices for both tasks.

The manager owns the machines and so can control workers' access to them. To maximize profit, the manager chooses how to assign workers to tasks: She can assign each worker to perform a single task (single-tasking *S*) or have them perform multiple tasks (multitasking *M*). The selection of production method will be formalized in the subsequent section. The manager can direct this assignment because she controls workers' access to the machines. Workers make task-specific human capital investments by accessing task-specific machines under a given production method. If a worker cannot access a task-specific machine, he cannot organize his private best practice of how to perform his given task. Thus, a manager has to decide a production method that induces a worker's optimal investments in task-specific knowledge given his predefined skill sets.

Technology and Production Method. To produce a good, two equally important but different tasks A and B must be performed and task-specific machines K_A and K_B are used, respectively. Each machine K_i requires the amount of labor input x_i, i=A,B, to contribute to production. This paper assumes that each machine has a constant marginal productivity with respect to labor and that the marginal productivities are the same. This paper normalizes their marginal productivities equal to one; thus, effective inputs are x_1 and x_2. For production technology, this paper assumes the Leontief production function in terms of tasks to reflect the strong complementarity between tasks in production.[3] As Becker and Murphy (1992) point out, even the most commonplace goods consist of a number of tasks, and firms must combine those tasks to produce the goods. Thus, given x_A and x_B, the quantity is $q = \min\{x_A, x_B\}$. Workers make task specific investments on their tasks. For example, although professors have sufficient knowledge on the subject from their Ph.D. trainings, they additionally need to prepare for the classes they teach by making class notes and developing an effective teaching method. They can keep their preparation results and are compensated for their teaching method. To teach different classes, professors need to develop different investment on the task. Worker 1 makes his task-specific investment $e_1 = (a_1, b_1)$ where $(a_1, b_1) \in [0, \infty)^2$. Similarly, Worker 2 makes his specific investment $e_2 = (a_2, b_2)$ where $(a_2, b_2) \in [0, \infty)^2$. The input levels x_A and x_B, therefore, are equal to $a_1 + a_2$ and $b_1 + b_2$, respectively. The price of this good is normalized to 1. The revenue of

[3] This paper assumes that tasks are strictly complementary. Substitutable tasks imply that a firm has “redundant” tasks in production, and a production function should reflect the maximal value of input use. This paper, however, assume that productive inputs can be substitutable.

the manager is $R(e_1, e_2) = \min\{a_1 + a_2, b_1 + b_2\}$. In this setup, single-tasking S can be represented as $\{(a_1, 0), (0, b_2)\}$; multitasking M can be represented as $\{(a_1, b_1), (a_2, b_2)\}$. The following table summarizes the aforementioned technology.

Table 2.1. Technology and Production Method

	Task A	Task B
Machine	K_A	K_B
Worker 1	$a_1 \geq 0$	$b_1 \geq 0$
Worker 2	$a_2 \geq 0$	$b_2 \geq 0$
Input	$x_A = a_1 + a_2$	$x_B = b_1 + b_2$

Incomplete Contract and Sequence of Events. This paper modifies the setup of property rights literature (Hart and Moore 1990; Rajan and Zingales 1998). At date 0, the manager chooses a production method $PM \in \{S, M\}$. Regarding the contractibility of a production method, this paper assumes that the production method choice is a manager's unilateral investment decision. In Section 2.7.1, this paper examines the case that the production method is contractible. The production method as a unilateral investment captures a firm's long-term decision, such as the comprehensive reorganization of its production system. In this case, workers face severe liquidity constraints to negotiate the decision, whereas a firm can have enough financial recourse to implement a production method.

The decision incurs two types of fixed costs to implement the chosen production method: the costs of adapting workers to facilities and of coordinating work flow. The composition of fixed costs can vary with production method. First, a firm incurs the costs of adjustment because it needs to provide workers with task-specific training and to prevent workers' accidents incurred by the change in the contents of their work. For example, under single-tasking, a manger needs to prevent accidents caused by performing boring tasks repetitively; under multitasking, a manager needs to prevent accidents from switching tasks improperly. The amount of the on-the-job training can also differ. Usually, multitasking requires more on the job training (Osterman 1999). Second, a firm needs to facilitate and coordinate workflow. To do so, a firm invests in additional facilities to enhance the flow of information between tasks and adjusts the layout of machine and tools in a plant. The facilities and plant layout also vary depending on how labor is used in production. For example, multitasking can require flexible machine tools; single-tasking can require automatic machines that perform fixed functions with high precision. Let F_S and F_M be the fixed cost of implementation of single-tasking and multitasking, respectively. This paper defines the fixed cost differential $F \in (-\infty, \infty)$ as $F \equiv F_M - F_S$.

After a production method is chosen, workers choose their level of task-specific investments between date 0 and date 1 (Rajan and Zingales 1998). Their investments are not contractible. The task-specific investment represents workers' investments to develop their private best practice to perform tasks. For example, workers try to learn to efficiently use task-specific-machines and the operation rules of the tasks. Worker 1 invests $e_1 = (a_1, b_1)$ and worker 2 invests $e_2 = (a_2, b_2)$. Workers choose their investment levels non-cooperatively.

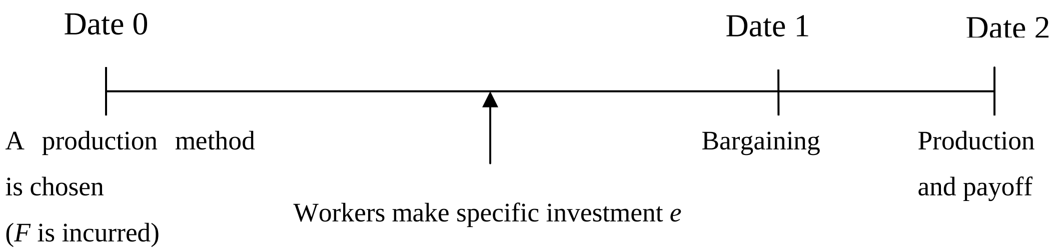
At date 1 all aspects of the relationship become contractible. Therefore, a manager and workers can divide the revenue at date 2 through bargaining at date 1. Following Hart and Moore (1990) and Rajan and Zingales (1998), this paper adopts the Shapley value as the solution concept in the date 1 bargaining and assumes that a manager and workers have outside options with zero value. The Shapley value $B_j,\ j = M, 1, 2$ under a given production method $PM \in \{S, M\}$ is

$$B_j(e_1, e_2 \mid PM) = \sum_{S \mid j \in S} p(S)[v(S \mid e_1, e_2, PM) - v(S \setminus \{j\} \mid e_1, e_2, PM)],\ j = M, 1, 2\ ,$$

where S is a coalition from $\{M, 1, 2\}$ and $p(S)$ is the probability that a coalition S arises as the union of j and its predecessors in a random ordering: It is represented as $(I - \#S)!(\#S - 1)!/I!$, where I is the total number of players in the grand coalition and #S is the number of players in the coalition *S*. Finally, a coalition S chooses an efficient ex post allocation (Hart and Moore 1990); therefore, $v(S \mid e_1, e_2, PM)$ represents the maximum value of the coalition S given investment levels e_1, e_2 and a production method. This paper assumes that the investments become useless outside a firm. Thus, a manager and workers do not have outside options in the date 1 bargaining.

At date 2, workers produce. A manager and workers divide the revenue based on the date 1 contract. In this stage, this paper assumes that the workers' production costs are zero due to their task-specific investment at date 1. The payoff is expressed in date 0 dollars. All parties are risk neutral. Timeline is as follows:

Figure 2.1. Timeline



Payoffs. The manager's ex ante payoff U_M and each worker's ex ante payoff U_i, i=1,2 are as follows:

$$\text{Manager:} U_M = B_M(e_1, e_2 \mid PM) - F$$

$$\text{Worker } i\text{:} U_i = B_i(e_1, e_2 \mid PM) - g_i(e_i \mid PM)$$

where $PM \in \{S, M\}$, B_M is the Shapley value of the manager, B_i, $i = 1,2$ is the Shapley value of a worker and $e_1 = (a_1, b_1), e_2 = (a_2, b_2)$ are workers' investments, and $g_i(e_i \mid PM)$ is a cost function of a worker $i = 1,2$. The cost function is

$$g_i(a_i, b_i \mid PM) = \frac{1}{2}\left(\frac{a_i}{\lambda}\right)^2 + \frac{1}{2}\left(\frac{b_i}{\lambda}\right)^2 + ka_ib_i = \frac{1}{2\lambda^2}\left(a_i + b_i\right)^2 - \left(\frac{1}{\lambda^2} - k\right)a_ib_i,$$

where $\lambda \in [1, \infty)$ and $k \in [0,1)$. This paper assumes that the cost function is convex (i.e., positive definite) in task-specific investments and that $1/\lambda^2 > k$. The parameters λ and k characterize the type of a worker in terms of skill composition. Regarding the previous teaching example, we can accept that the λ can reflect the amount of knowledge in his major field and that the k can represent his ability to straddle two different fields. This paper assume that the investments do not accumulate on the λ and k; therefore, the choice of production method does not affect workers' outside options.

Workers have specific and general skills. Specific skills enable a worker to develop his best practice with less amount of investment. The parameter $\lambda \in [1, \infty)$ represents the single-tasking efficiency. The parameter $\lambda = 1$ implies no efficiency when he is performing an individual task. Specific skills influence the efficiency parameter λ. For example, the higher the specific skills a worker has, the larger λ is and the less costly a worker's development of his operational know-how is.

Workers incur an additional cost if they perform two tasks simultaneously. A worker with a high general skill can perform two tasks with less additional cost. The cost of flexibility parameter $k \in [0,1)$ represents the cost of simultaneously investing in two tasks. For example, in multitasking, a worker's marginal investment cost is $(1/\lambda^2)a_i + kb_i$. The parameter $k = 0$ implies that a worker can switch between tasks with zero cost. The higher general skill a worker has, the lower k is and the less costly a worker's performance of multiple tasks is. This paper assumes that the value of k is less than one because there can be some gains when a worker performs multiple tasks. The source of gains can be either the "preference for variety" of workers (Besanko, Regibeau and Rockett 2005) or the "multitask learning" during the performance of multitasks (Lindbeck and Snower 2000).

The cost function indicates that workers are identical and symmetric in the sense that they can perform each task equally well and simultaneously perform two tasks at the same cost. The relative magnitudes of two parameters decide the type of workers. If $\lambda^2 k$ is "large," then this paper regards workers as specialists; conversely, if $\lambda^2 k$ is "small," then this paper regards workers as generalists. The precise definition of being small and large depends on the contexts.

The method of allocating workers' labor across separate, complementary tasks influences the payoff functions of a manager and workers in two aspects: the productivity aspect and the bargaining aspect. First, there is productivity trade-off between volume and marginal cost. Single-tasking uses one worker per task with lower marginal investment cost $(1/\lambda^2)a_i$, whereas multitasking uses two workers per task with higher marginal investment cost $(1/\lambda^2)a_i + kb_i$. Second, a production method can change marginal contributions of workers to grand coalition and sub-coalitions in the opposite direction due to the bottleneck externality. In single-tasking, a worker's absence can be a bottleneck to other workers' productivity as well as a direct reduction of the worker's investment. The worker's absence increases his marginal contribution to grand coalition, but decreases his contribution to sub-coalition. In the former case, the worker is a bottleneck to grand coalition; in the latter case, his partner is a bottleneck to sub-coalition. In multitasking, however, a worker's absence implies only the reduction of the worker's investment. Compared to single-tasking, the absence reduces the worker's contribution to grand coalition, but increases his contribution to sub-coalition because no one can be a bottleneck to his partner.

2.5. Results

This section shows that multitasking is socially optimal because it uses two workers who efficiently allocate their investment over two tasks absent bargaining power issue. However, single-tasking can be equilibrium with the bargaining power effect on production because it reduces workers' marginal costs and provides workers with strong bargaining power and incentives to invest in tasks thereof.

2.5.1. First Best Production Method

In this section, we show that multitasking is the socially optimal production method, but that multitasking requires a larger total investment from each worker relative to single-tasking. The social surpluses under single-tasking $TS(e_1, e_2 \mid S)$ and under multitasking $TS(e_1, e_2 \mid M)$ are

$$TS(e_1, e_2 \mid S) = \min\{a_1, b_2\} - \frac{1}{2\lambda^2} a_1^2 - \frac{1}{2\lambda^2} b_2^2$$

$$TS(e_1, e_2 \mid M) = \min\{a_1 + a_2, b_1 + b_2\} - \frac{1}{2\lambda^2}\left(a_1^2 + b_1^2\right) - ka_1b_1 - \frac{1}{2\lambda^2}\left(a_2^2 + b_2^2\right) - ka_2b_2 .$$

This paper defines the first best production method as a method that satisfies

$$\max_{\{S,M\}}\{\max_{e_1,e_2} TS(e_1, e_2 \mid S), \max_{e_1,e_2} TS(e_1, e_2 \mid M)\} .$$

PROPOSITION 1. *Suppose that* $F = 0$ *and that* $\lambda^2 k < 1$. (a) *Multitasking is the socially optimal production method. (b) Each worker always makes more total investment under multitasking than under single-tasking.*

PROOF. See Appendix A. □

If there is neither fixed cost differential nor bargaining issues in production, multitasking can achieve the maximum total surplus. This is intuitive, because a firm has both workers on each task and workers' cost function is convex. Suppose that workers are performing single-tasking and that a social planner chooses to shift to multitasking. Multitasking can optimally allocate workers' investments over tasks. It also allows workers to reduce their high level of investment on the single task and begin to invest in the other task. Because of the convex cost structure, workers are able to make a considerable amount of investment in the new task with relatively less reduction of investment in the old task. Moreover, two workers are performing both tasks in multitasking. Thus, despite workers' cost of being flexible in multitasking, social surplus in multitasking will be higher than in single tasking. In addition, under the condition that the cost of flexibility is not too large (i.e., $\lambda^2 k < 1$), all workers are making higher total investments in multitasking than in single-tasking. However, if workers have very high single-tasking efficiency λ and high cost k of flexibility that make $\lambda^2 k$ close to one, the advantage of multitasking over single-tasking in generating social surplus will be reduced.

In the second best world in which bargaining power can influence workers' incentives to make investments, single-tasking can arise as equilibrium. Single-tasking will allow workers to have strong hold-up power in the bargaining stage, whereas multitasking will reduce workers' bargaining power. This change in workers' bargaining power can lead to productivity gains because workers' incentives to invest in tasks become larger in single-tasking. In subsequent sections, this paper examines how the productive efficiency and bargaining power of workers influence the choice of production method and the distribution of earnings.

2.5.2. Single-tasking *S*

This section examines the second best outcome under single-tasking. In the second best case, a manager will face a strong hold-up power as well as productive efficiency of workers. By choosing single-tasking, the manager enforces workers 1 and 2 to make specific investments in the form of $\{(a_1,0),(0,b_2)\}$. Thus, $g_1(a_1,0\,|\,S)=(1/2)(a_1/\lambda)^2$ and $g_2(0,b_2\,|\,S)=(1/2)(b_2/\lambda)^2$. The manager's revenue $R(e_1,e_2)$ is $\min\{a_1,b_2\}$ under single-tasking.

At date 2, given specific investments $e_1=(a_1,0)$ and $e_2=(0,b_2)$ from date 1, the manager and workers 1 and 2 produce the good and divide the revenue according to their Shapley values as they agreed at date1. The Shapley value of each player is $B_j=(1/3)\min\{a_1,b_2\},\ j=M,1,2$. Workers 1 and 2's ex ante payoffs are as follows:

$$U_1(e_1,e_2\,|\,S)=\frac{1}{3}\min\{a_1,b_2\}-\frac{1}{2}\left(\frac{a_1}{\lambda}\right)^2,$$

$$U_2(e_1,e_2\,|\,S)=\frac{1}{3}\min\{a_1,b_2\}-\frac{1}{2}\left(\frac{b_2}{\lambda}\right)^2.$$

Because the solution concept is a Nash Equilibrium, multiple equilibria are expected. Thus, this paper adopts the notion of the "best" equilibrium.

DEFINITION. The *best equilibrium* is an equilibrium in which workers payoffs are higher than in any other equilibrium.

LEMMA 1. *At all equilibria under single-tasking,* $a_1^*=b_2^*$. *Moreover,* $a_1^*=b_2^*=\lambda^2/3$ *is the unique best equilibrium under single-tasking.*

PROOF. See Appendix A. □

From the lemma 1, the best equilibrium payoffs $U_1(e_1^*,e_2^*\,|\,S)$ and $U_2(e_1^*,e_2^*\,|\,S)$ of workers 1 and 2 are $(1/3)a_1^*-(1/2)(a_1^*/\lambda)^2$ and $(1/3)b_2^*-(1/2)(b_2^*/\lambda)^2$, respectively. Under single-tasking, the best equilibrium investment $\{(a_1^*,0),(0,b_2^*)\}$ is $\{(\lambda^2/3,0),(0,\lambda^2/3)\}$. A manager and workers evenly divide their equilibrium revenue, which is $\lambda^2/3$: The equilibrium wage is $\lambda^2/9$ for each worker and the equilibrium profit for (M) is $\lambda^2/9$. Finally, the ratio R_S of the (M)'s profit to total wage bill is $1/2$.

In this single-tasking method, each player has the same significance in the production: The manager provides the machines, and each worker can hold up the manager and the other worker in production because of the separation of complementarity of tasks. Especially, one worker in task A can make the other worker's labor in task B useless by refusing to work. When a worker refuses to make his investment, he reduces not only his investment, but also other workers' productive input. Thus, in addition to the reduction of his own labor supply, worker 1 can be a bottleneck to production. In an extreme case, such as the Leontief production, worker 1 can stop production. However, the marginal cost of specific investment (e.g., $\left(1/\lambda^2\right)a_1$ for worker 1) can be low enough for a manager to induce his investment easily.

The payoff function of a worker shows the trade-off between productivity and bargaining that a manager faces. Because he can concentrate on a single task and faces lower marginal cost under single-tasking than under multitasking, a worker is more likely to make a higher specific investment. However, by exerting the bottleneck externality, a worker can extract larger gains from a manager: Specialization increases a worker's contribution to grand coalition with a higher weight and reduces his contribution to sub-coalition with a lower weight.

To illustrate the trade-off in single-tasking, let's rearrange the equilibrium payoff $(1/3)a_1^* - (1/2)(a_1^*/\lambda)^2$ of worker 1 as

$$(1/3)(a_1^* - 0) + (1/6)(0 - 0) - (1/2)(a_1^*/\lambda)^2 .$$

The first term implies that worker 1 can increase his contribution to grand coalition because he can stop production. Conversely, he will lose his contribution to sub-coalition because he cannot produce without other players. Because the weight of the former is higher, a manager faces the strong bargaining power of a worker. The manager, however, can also gain because she can more easily induce a worker's specific investment due to his decreased marginal cost. Thus, total investments of workers in production and a manager's profit can also become larger.

2.5.3. Multitasking *M*

In this section, we examine the second-best multitasking outcome. Under the second-best multitasking, a manager lessens workers' hold-up power but can increase their marginal costs. By choosing the multitasking method, a manger allows workers 1 and 2 to access both machines to enhance the flexibility of the use of labor. Workers make their investments over tasks in the form of $\{(a_1,b_1),(a_2,b_2)\}$. Thus, worker 1's and worker 2' costs are

$$g_1(a_1,b_1\,|\,M) = 1/2\left(a_1/\lambda\right)^2 + 1/2\left(b_1/\lambda\right)^2 + ka_1b_1$$

$$g_2(a_2,b_2\,|\,M) = 1/2\left(a_2/\lambda\right)^2 + 1/2\left(b_2/\lambda\right)^2 + ka_2b_2 .$$

The manager's revenue $R(e_1,e_2)$ is $\min\{a_1+a_2, b_1+b_2\}$ under the multitasking method.

Given investments $e_1=(a_1,b_1)$ and $e_2=(a_2,b_2)$ from date 1, the manager and workers 1 and 2 produce the good and divide the revenue according to their Shapley values. Each player's Shapley value is different. The value B_M of manager is

$$B_M = 1/3\min\{a_1+a_2, b_1+b_2\} + 1/6\min\{a_1,b_1\} + 1/6\min\{a_2,b_2\} .$$

The values of worker 1 and 2, however, are

$$B_1 = 1/3\left(\min\{a_1 + a_2, b_1 + b_2\} - \min\{a_2, b_2\}\right) + 1/6\min\{a_1, b_1\}$$

$$B_2 = 1/3\left(\min\{a_1 + a_2, b_1 + b_2\} - \min\{a_1, b_1\}\right) + 1/6\min\{a_2, b_2\}.$$

Whereas a manager is still critical in the production of the good, the importance of individual workers has changed because they become "smoothly" substitutable in the production of the good; the manager and the other worker can form an alternative productive coalition if one worker tries to hold up production. Therefore, multitasking reduces a worker *i*'s contribution to the grand coalition by $\left(1/3\right)\min\{a_j, b_j\}$ and increases his contribution to sub-coalition by $\left(1/6\right)\min\{a_i, b_i\}$ compared to single-tasking. Because the weight of his contribution to the grand coalition is bigger, an individual worker's share is likely to decrease. But in multitasking, a manager uses two workers' labor in each task. The method may increase total investments in production and the size of revenue. The Shapley value of workers, therefore, depends on how much investment the worker can make in tasks. Marginal cost $\left(1/\lambda^2\right)a_i + kb_i$ of specific investment influences the amount of investments that the worker *i* will make. Workers 1 and 2's ex ante payoffs are as follows:

$$\begin{aligned} U_1(e_1, e_2 \mid M) = {} & 1/3\min\{a_1 + a_2, b_1 + b_2\} + 1/6\min\{a_1, b_1\} - 1/3\min\{a_2, b_2\} \\ & -[1/2\left(a_1/\lambda\right)^2 + 1/2\left(b_1/\lambda\right)^2 + ka_1b_1] \end{aligned}$$

$$\begin{aligned} U_2(e_1, e_2 \mid M) = {} & 1/3\min\{a_1 + a_2, b_1 + b_2\} + 1/6\min\{a_2, b_2\} - 1/3\min\{a_1, b_1\} \\ & -[1/2\left(a_2/\lambda\right)^2 + 1/2\left(b_2/\lambda\right)^2 + ka_2b_2] \end{aligned}.$$

As in the single-tasking case, multiple equilibria are expected in a multitasking situation. The following lemma 2 gives the characterization of those equilibria. Then, this paper adopts the notion of the best equilibrium as in the single-tasking case.

LEMMA 2. *At all equilibria under multitasking,* $a_1^* + a_2^* = b_1^* + b_2^*$. *Moreover,* $a_i^* = b_i^*, i = 1,2$ *is the unique best equilibrium.*

PROOF. See Appendix A.□

From lemma 2, the best equilibrium payoffs $U_1(e_1^*, e_2^*)$ and $U_2(e_1^*, e_2^*)$ of worker 1 and 2 are $(1/2)a_1^* - (1/\lambda^2 + k)a_1^{*2}$ and $(1/2)b_1^* - (1/\lambda^2 + k)b_1^{*2}$, respectively. Because the equilibrium payoff functions are concave in investment levels, the optimum investments under multitasking are $a_1^* = b_1^* = \frac{1}{4(1/\lambda^2+k)}$ and $a_2^* = b_2^* = \frac{1}{4(1/\lambda^2+k)}$ from the first order conditions. Workers' total investment levels are $a_1^* + b_1^* = a_2^* + b_2^* = \frac{1}{2(1/\lambda^2+k)}$. From the equilibrium revenue $R(e_1^*, e_2^*) = \frac{1}{2(1/\lambda^2+k)}$, the manager and workers obtain their parts: the wage $B_i(e_1^*, e_2^*)$ for each worker $i = 1,2$ will be $\frac{1}{8(1/\lambda^2+k)}$ and the profit $B_M(e_1^*, e_2^*)$ will be $\frac{1}{4(1/\lambda^2+k)}$. Finally, the ratio R_M of the manager's profit to the total wage bill is $1 - 4\left[\lambda^2/(1+\lambda^2 k)\right]F$, which depends on the fixed cost differential F.

To illustrate the tradeoff between productivity and bargaining power, let's rewrite the equilibrium payoff $(1/2)a_1^* - (1/\lambda^2 + k)a_1^{*2}$ of worker 1 as follows:

$$(1/3)(a_1^* + a_2^* - a_2^*) + (1/6)(a_1^* - 0) - (1/\lambda^2 + k)a_1^{*2}$$

Adoption of multitasking reduces his contribution to grand coalition because a manager and the other worker can form a productive coalition. Multitasking increases his contribution to sub-coalition because worker 1 can now form a productive coalition with a manager. The weights on contributions are $1/3$ and 1/6, respectively. In both contributions, a worker can influence production only by the amount of his investment; he can no longer exert the bottleneck externality on production. Depending on the marginal cost, the size of each contribution and the compensation of worker 1 vary. A worker will make less investment in each task because he needs to split his capacity over two tasks and incurs an additional cost. The total investments of each worker in production, however, depend on parameters λ^2 and k.

2.5.4. Choice of a Production Method

When a manager unilaterally decides on a production method at date 0, she examines ex-post profit because workers cannot propose an alternative method and side payment due to their wealth constraints. We will show that a manager selects an equilibrium production method by comparing her Shapley value and the fixed cost differential.

The manager will not adopt a specific method if the fixed costs relevant to the method exceed her share of revenue that the method can generate; therefore, the cost differential is bounded. Because $\pi_S = \lambda^2/9$ and $\pi_M = \lambda^2/4(1+\lambda^2 k)$ from the previous section, the ranges of fixed costs that the manager is willing to consider are $F_S \in [0, \lambda^2/9]$ and $F_M \in [0, \lambda^2/4(1+\lambda^2 k)]$, respectively. Therefore, the range of fixed cost differential F that the manager is willing to consider is $[-\lambda^2/9, \lambda^2/4(1+\lambda^2 k)]$.

From the previous discussion, we can summarize the outcomes of the best equilibrium under each method:

Table 2.2. Variables in Equilibrium

	Single-tasking S	Multitasking M
Worker's Investment on Each Task	$\lambda^2/3$	$\lambda^2/4(1+\lambda^2 k)$
Worker's Total Investment (a_1+b_1 and a_2+b_2)	$\lambda^2/3$	$\lambda^2/2(1+\lambda^2 k)$
Production/Revenue	$P_S=\lambda^2/3$	$P_M=\lambda^2/2(1+\lambda^2 k)$
Profit	$\pi_S=\lambda^2/9$	$\pi_M=\lambda^2/4(1+\lambda^2 k)-F$
Wage	$w_S=\lambda^2/9$	$w_M=\lambda^2/8(1+\lambda^2 k)$
Earnings Differential (Ratio of Profit to Total Wage Bill)	$R_S=1/2$	$R_M=1-4\left[\lambda^2/(1+\lambda^2 k)\right]F$

Remark. If the costs of implementing single-tasking and multitasking are the same, i.e., the differential F is zero, a manager always prefers multitasking to single-tasking because $\lambda^2 k<1$. The manager chooses a socially inefficient single-tasking only when the cost F of implementing multitasking is relatively high and workers cannot offer side payment.

When a firm unilaterally decides how to use workers' labor in production, it compares profits from both methods, taking into account a manager's Shapley value and the fixed cost differential. A manager compares her profit $\lambda^2/9$ under single-tasking and $[\lambda^2/4(1+\lambda^2 k)]-F$ under multitasking where $F\in[-\lambda^2/9,\lambda^2/4(1+\lambda^2 k)]$ to adopt the production method. If the cost differential is sufficiently low relative to the profit differential between the methods, the manager will select multitasking; otherwise, she will select single-tasking. The following lemma confirms this supposition.

LEMMA 3. *Suppose that the best equilibrium outcome is an interior solution under each production method. Let the lower bound* $-\lambda^2/9$ *of F be* F_L *and the upper bound* $\lambda^2/4(1+\lambda^2 k)$

of F *be* F_U *. There exists a positive number* $F_o(\lambda^2, k) \in (F_L, F_U)$ *such that the manager chooses multitasking if* $F \in [F_L, F_o]$ *and single-tasking if* $F \in (F_o, F_U]$.

PROOF. See Appendix A. □

The following two lemmas show how the type of workers' skill influences the choice criterion F_o and how technological progress affects the choice of a production method.

LEMMA 4. *If* k *decreases,* F_o *increases, and the manager is more likely to adopt multitasking ; If* λ^2 *increases with* $\lambda^2 k \leq 1/2$ *,* F_o *increases, and the manager is more likely to adopt multitasking for a given* F *. However, if* λ^2 *increases with* $\lambda^2 k > 1/2$ *,* F_o *decreases, and the manager is more likely to adopt single-tasking for a given* F *.*

PROOF. See Appendix A. □

Lemma 4 implies that workers' schooling and training prior to their employment can influence how a firm decides to use labor in production. Efficiency and flexibility parameters reflect the types of skills that workers have when firms hire them. The low cost k of flexibility indicates that a worker has a high general skill in the sense that he is good at simultaneously performing multiple tasks; the high efficiency parameter λ indicates that a worker is skilled at organizing his best practice in performing a specific task. With the interpretation on parameters, lemma 4 implies that the type of workers available in an economy can influence firms' selection of production method. If workers are generalists, then the firm is more likely to adopt multitasking given a current technological condition. If workers are specialists, the firm's choice depends on the relative composition of workers' skill sets: a firm is more likely to adopt multitasking if the relative composition of the specific skill is not so high. However, if the relative composition becomes high, a firm is more likely to adopt single-tasking.

LEMMA 5. *If technological progress decreases F ("multitasking-biased technological change"), the manager is more likely to adopt multitasking; conversely, if technological progress increases F ("single-tasking-biased technological change"), the manager is more likely to adopt single-tasking.*

PROOF. In both cases, F_o depends on parameters λ and k only. For given F_o, multitasking-biased technological change reduces the fixed cost differential F; conversely, single-tasking-biased technological change increases F. □

Lemma 5 implies that the type of the implementation cost that technological progress reduces will influence how to use labor in production. Lemma 5 suggests that when researching the effect of technology on organization, we need to specify the type of the cost that technological progress is reducing. Let's consider the development of information technology (IT). If IT enables a firm to combine tools into one machine with a common "platform," a flexible machine tool for instance, then the implementation cost of multitasking will decrease. However, if IT enhances the precision and speed of a machine tool that is only task-specific, then the implementation cost of single-tasking will decrease, but the cost of multitasking will not be affected much.

2.5.5. Division of Labor and the Distribution of Earnings

This section will show that a worker with the same skill composition can earn different wages in the single-tasking and multitasking equilibrium and that the relative profit of a manager can increase with the shift from single-tasking to multitasking. Proposition 2 demonstrates that specialists earn higher wages in single-tasking and that generalists earn higher wages in multitasking.

PROPOSITION 2. *(a) If* $\lambda^2 k \geq 1/8$*, then* $w_S \geq w_M$. *(b) If* $\lambda^2 k < 1/8$*, then* $w_S < w_M$.

PROOF. Because equilibrium wages are $w_S = \lambda^2/9$ and $w_M = \lambda^2/8(1+\lambda^2 k)$, direct comparison of the wages gives the results. □

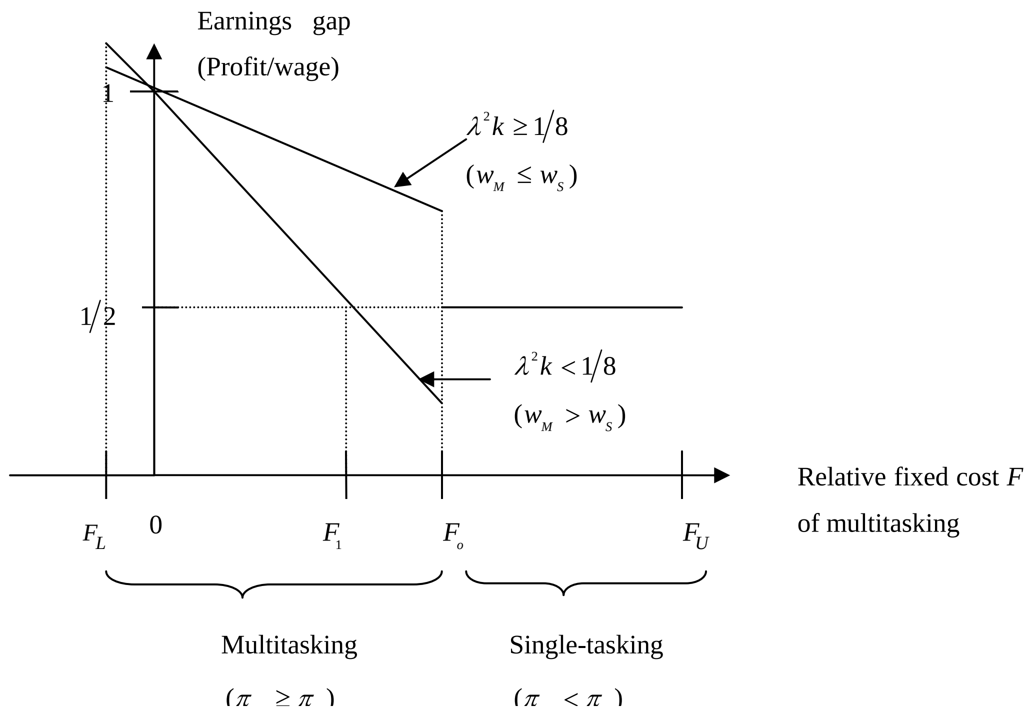
Proposition 2 implies that a firm's selection of a production method, whether to use their labor task-specifically or flexibly, can differentiate the compensation of workers with the same skills. When workers are specialists (i.e., $\lambda^2 k \geq 1/8$), a firm that uses single-tasking can provide higher wages than a firm that uses multitasking: When workers are generalists (i.e., $\lambda^2 k < 1/8$), a firm that uses workers' labor flexibly can pay higher wages than a firm that uses workers' labor task-specifically. The proposition can provide an explanation on the "inter-industry wage differential" results (Krueger and Summers 1988; Groshen 1991). Wages in an industry in which the majority of firms are adopting single-tasking can differ from those in an industry in which the majority of firms are adopting multitasking production methods even if workers have similar skill composition. The next proposition shows that the adoption of multitasking can broaden the earnings gap between a manager and workers.

PROPOSITION 3. *Suppose that the fixed cost differential decreases from* $F \in (F_o, F_U]$ *to* $F' \in [F_L, F_o]$ *(i.e., a firm shifts its production method from single-tasking to multitasking). (a) If* $\lambda^2 k \geq 1/8$*, then earnings differential between a manager and workers will widen under* *multitasking. Let* $\lambda^2/8(1+\lambda^2 k) \in (0, F_o)$ *be* F_1. *(b) If* $\lambda^2 k < 1/8$ *and* $F' \in [F_L, F_1]$, *then the earnings differential between the two will widen under multitasking. (c) If* $\lambda^2 k < 1/8$ *and* $F' \in (F_1, F_o]$, *then the earnings differential will narrow under multitasking.*

PROOF. See Appendix A. □

A manager will choose multitasking because the cost differential *F* is lower than the cut-off fixed cost F_o. If workers are specialists ($\lambda^2 k \geq 1/8$), the shift will render workers' compensation smaller under multitasking than under single-tasking, as Proposition 2 shows. A manager will shift from single-tasking to multitasking only if the shift is profitable. Because this paper measures the earnings differential between management and workers by the ratio of profit to total wage bill, the shift from single-tasking to multitasking will widen the earnings gap between management and workers. Alternatively, if workers are generalists ($\lambda^2 k < 1/8$), they can earn higher wages under multitasking than under single-tasking. Thus, the change in the ratio of profit to total wage bill depends on the fixed cost of multitasking because a manager's profit consists of her Shapley value and the fixed cost. If multitasking is not expensive to implement, the earnings differential still widens. The increase in profit is larger than the increase in workers' compensation. If multitasking is expensive to implement, the earnings differential narrows after shifting from single-tasking to multitasking. The increase in profit is smaller than the increase in workers' compensation. The following figure illustrates the results.

Figure 2.2. The division of labor and the earnings gap: from S to M



The slopes are the lower bounds of the ratio $R_M = 1 - 4\left[\lambda^2/(1+\lambda^2 k)\right]F$ of profit and total wage bill under multitasking when workers are specialists and generalists. The upper slope is when workers are specialists and is always higher than $1/2$. The bottom slope is when workers are generalists and is lower than $1/2$. When workers are specialists (i.e., upper slope), the shift from single-tasking to multitasking always widens the earning gap. When workers are generalists (i.e., bottom slope), the shift can narrow the gap over the range $[F_1, F_o]$. This is because the profit does not increase enough compared to the wage increase. Below F_1, the shift will widen the gap. Moreover, the gap will broaden even if workers earn higher wages.

Because technological progress changes the fixed costs of adopting a production method, we can derive the effect of technological progress on the distribution of earnings between management and workers. If workers are specialists, multitasking-biased technological change will widen the gap for any amount of savings that the technological progress generates. If workers are generalists and the savings are not sufficiently large, multitasking-biased technological change can narrow the gap. If workers are generalists and the savings are sufficiently large, multitasking-biased technological change will eventually widen the gap although a firm can provide workers with higher wages. The following corollary formalizes the derivation.

COROLLARY 1. *Suppose that multitasking-biased technological change keeps reducing the cost differential* F *below* F_o. *If* $\lambda^2 k \geq 1/8$, *technological change broadens the earnings gap between management and workers for any level of cost savings. If* $\lambda^2 k < 1/8$, *it compresses the dispersion of earnings over the range of* $(F_1, F_o]$ *and widens it over the range of* $[F_L, F_1]$. *In the latter range, the gap can widen even if workers earn higher wages.*

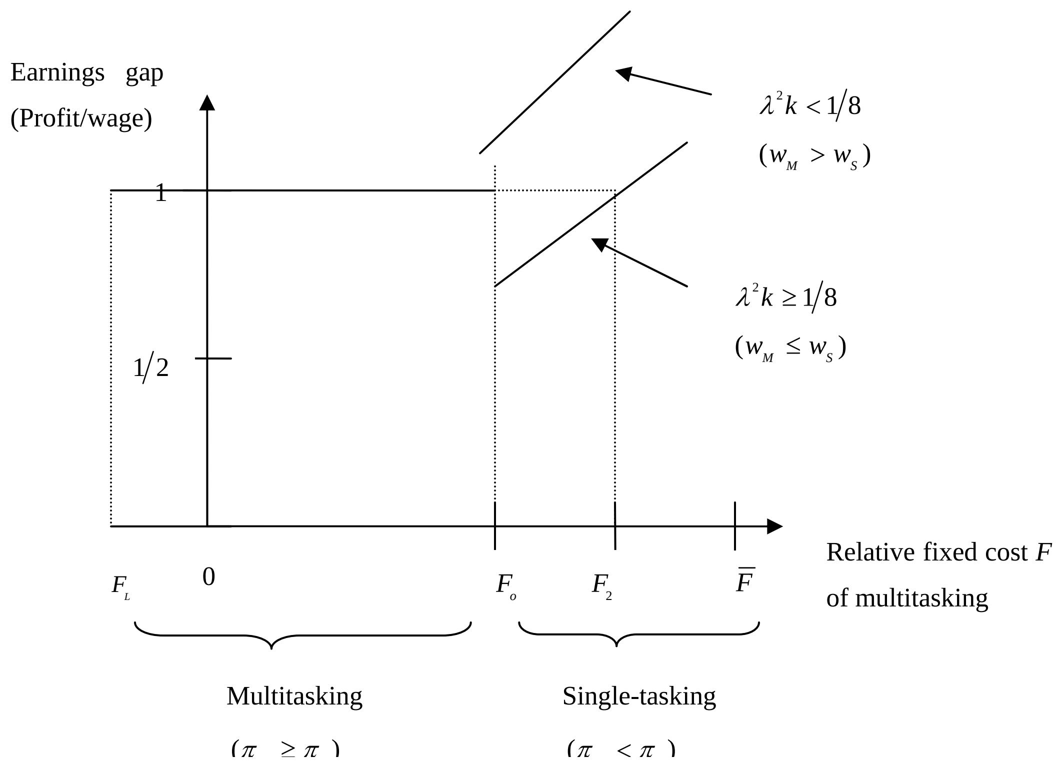
Corollary 1 also implies that the combination between the type of technological progress and the type of workers influences the change in the distribution of earnings between management and workers. Multitasking-enhancing technological change at least provides an opportunity of narrowing the gap if workers are generalists; if workers are specialists, however, technological change will always widen the gap.

Similar analysis can apply to the transition from multitasking to single-tasking except for the interpretation of the fixed cost differential F. It should be interpreted as the fixed cost advantage for single-tasking. Single-tasking-biased technological progress can compress the gap if workers are specialists and the fixed cost advantage is modest. However, it always will widen the gap when workers are generalists. The following corollary formalizes the intuitions.

COROLLARY 2. *Suppose that single-tasking-biased technological change keeps increasing the cost differential* F *above* F_o. *Let* $\lambda^2/9$ *be* F_2. *If* $\lambda^2 k \geq 1/8$ *and the fixed cost advantage F is in the range of* $(F_o, F_2]$ *, technological change narrows the earnings gap between management and workers. If* $\lambda^2 k \geq 1/8$ *and the fixed cost advantage F is in the range of* $(F_2, F_U]$, *technological change widens the earnings gap between management and workers. If* $\lambda^2 k < 1/8$, *technological change always widens the earnings gap.*

The following figure illustrates Corollary 2. The slope indicates two cases of the ratio $R_S = 1/2 + \left(9/2\lambda^2\right)F$. The upper slope indicates when workers are generalists, and the bottom slope indicates when workers are specialists. The bottom slope demonstrates that single-tasking-biased technological change can narrow the earnings gap between a manager and specialists in the range $(F_{o,} F_2]$.

Figure 2.3. The division of labor and the earnings gap: from M to S



2.6. Robustness

2.6.1. Multiple Workers on a Single Task: Four-worker Case

This section shows that the negative externality that a worker can exert due to the separation of complementary tasks will not disappear even if a worker has his substitutes and cannot stop production under single-tasking. This is because the dislocation of the worker still can be a bottleneck to production. By adopting the multitasking method, a manager can prevent this negative externality.

To clarify this point, this paper considers a four-worker example: Under single-tasking, the manager allocates two identical workers to each task and directs each worker to do only a single task. Under multitasking, the manager allows each worker to make his investment over the multiple tasks. The market demand is assumed to be large enough so that all the goods produced are sold and that the firm can hire four workers.

Single-tasking. Among six cases of allocating four workers evenly in two tasks , this paper considers a case in which workers 1 and 3 are allocated to task A and workers 2 and 4 to task B. The same analysis can be applied to other cases. Worker 1 obtains his Shapley value as his wage w_1 such that

$$
\begin{aligned}
w_1 = {} & \frac{1}{5}[\min\{a_1 + a_3, b_2 + b_4\} - \min\{a_3, b_2 + b_4\}] + \frac{1}{5\times 4}[\min\{a_1 + a_3, b_2\} - \min\{a_3, b_2\}] + \\
& \frac{1}{5\times 4}[\min\{a_1, b_2 + b_4\} - \min\{0, b_2 + b_4\}] + \frac{1}{5\times 4}[\min\{a_1 + a_3, b_4\} - \min\{a_3, b_4\}] + \\
& \frac{1}{5\times 6}[\min\{a_1, b_2\} - \min\{0, b_2\}] + \frac{1}{5\times 6}[\min\{a_1 + a_3, 0\} - \min\{a_3, 0\}] + \\
& \frac{1}{5\times 6}[\min\{a_1, b_4\} - \min\{0, b_4\}]
\end{aligned}
$$

Workers 2, 3 and 4 earn wages in a similar form with worker 1's wage. We can observe that coalitions including worker 1 belong to one of two types: a "productive" coalition or a "bottlenecked" coalition. This paper defines the productive coalition as a coalition in which workers are evenly allocated across two tasks. $\{(a_1, a_3), (b_2, b_4)\}$ and $\{a_1, b_2\}$ are examples of the productive coalitions. This paper defines the bottlenecked coalition as a coalition in which at least one worker's labor is not used efficiently due to the absence of his "pair." $\{(a_1, a_3), b_2\}$ and

$\{a_1, 0\}$ are examples of the bottlenecked coalitions. Under single-tasking, the dislocation of a worker transforms a productive coalition into a bottlenecked coalition and vice versa. Especially in the former case, not only can the dislocation of a worker in the productive coalition eliminate the worker's own investment, but it also can make other members' investment less productive. For example, the marginal contribution of worker 1 in a productive coalition $\{(a_1, a_3), (b_2, b_4)\}$ is

$$[\min\{a_1 + a_3, b_2 + b_4\} - \min\{a_3, b_2 + b_4\}].$$

His contributions to the production are two-fold: to make his own investment and to transform a bottlenecked coalition $\{a_3, (b_2, b_4)\}$ into a productive one $\{(a_1, a_3), (b_2, b_4)\}$. In the previous two workers' case, worker 1 could stop the production. Now worker 1 cannot stop the production anymore because of his possible substitute, worker 3. However, he can negatively influence the productivity of workers 2 and 4 because his absence can transform his previously productive coalition into a bottlenecked one.

The existence of substitute workers in each task, however, increases the profit of the manager. In this four-worker case, the manager earns her Shapley value as her profit such that

$$\begin{aligned}\pi_S = &\frac{1}{5}\min\{a_1 + a_3, b_2 + b_4\} + \\ &\frac{1}{5\times 4}\min\{a_1 + a_3, b_2\} + \frac{1}{5\times 4}\min\{a_1 + a_3, b_4\} + \frac{1}{5\times 4}\min\{a_1, b_2 + b_4\} + \frac{1}{5\times 4}\min\{a_3, b_2 + b_4\} + \\ &\frac{1}{5\times 6}\min\{a_1, b_2\} + \frac{1}{5\times 6}\min\{a_1, b_4\} + \frac{1}{5\times 6}\min\{a_3, b_2\} + \frac{1}{5\times 6}\min\{a_3, b_4\}\end{aligned}$$

Because the manager has a substitute in each task, she can obtain positive production even if one worker is fired or quits: All the bottlenecked coalitions contribute to the manager's profit in some degree. Therefore, this paper expects that the ratio R_S of profit to total wage bill under single-tasking will increase as the number of workers in each task increases: The earnings differential between management and workers will be larger than in the two-worker case.

Multitasking. Because each worker is allowed to make his investment over two tasks, the wage w_1 of worker 1 is as follows:

$$w_1 = \frac{1}{5}[\min\{a_1 + a_2 + a_3 + a_4, b_1 + b_2 + b_3 + b_4\} - \min\{a_2 + a_3 + a_4, b_2 + b_3 + b_4\}] +$$
$$\frac{1}{5\times 4}\sum_{\substack{i,j\in\{2,3,4\}\\ i\neq i}}[\min\{a_1 + a_i + a_j, b_1 + b_i + b_j\} - \min\{a_i + a_j, b_i + b_j\}] +$$
$$\frac{1}{5\times 6}\sum_{i\in\{2,3,4\}}[\min\{a_1 + a_i, b_1 + b_i\} - \min\{a_i, b_i\}] + \frac{1}{5\times 4}[\min\{a_1, b_1\} - 0]$$

Because every coalition is a productive coalition, the marginal contribution of worker 1 is only his own investment in each productive coalition. His absence does not induce bottlenecked coalitions and does not affect the productivity of other workers' investment. Thus, the dislocation of worker 1 reduces the production "smoothly," which can weaken the bargaining power of workers as in the two-player case. In case of the profit of the manger, all possible productive coalitions contribute to her profit as shown below.

$$\pi_M = \frac{1}{5}\min\{a_1 + a_2 + a_3 + a_4, b_1 + b_2 + b_3 + b_4\} + \frac{1}{5\times 4}\sum_{\substack{i,j,k\in\{1,2,3,4\}\\ i\neq j\neq k}}\min\{a_i + a_j + a_k, b_i + b_j + b_k\} +$$
$$\frac{1}{5\times 6}\sum_{\substack{i,j\in\{1,2,3,4\}\\ i\neq j}}\min\{a_i + a_j, b_i + b_j\} + \frac{1}{5\times 4}\sum_{i\in\{1,2,3,4\}}\min\{a_i, b_i\}$$

Thus, this paper expects that the ratio R_M of the profit to the total wage bill under multitasking will not change as the number of workers increases.

Conjecture. This paper will calculate outcomes based on the conjecture on equilibrium: (a) under single-tasking, $a_1 + a_3 = b_2 + b_4$ and $a_1 = a_3, b_2 = b_4$: (b) under multitasking,

$a_1 + a_2 + a_3 + a_4 = b_1 + b_2 + b_3 + b_4$ and $a_i = b_i, i = 1,2,3,4$. Although these are not rigorously proved equilibrium outcomes, from the previous analysis these look like serious candidates for the best equilibrium. In addition, the fixed cost differential F is assumed to be zero because the choice of the production mode is not the main focus here. Under single-tasking, $w_i = (19/60)^2 \lambda^2, i = 1,2,3,4$ and $\pi_S = (11/15)(19/60)\lambda^2$. Thus, the ratio R_S of the profit to the total wage bill is $11/19$. This ratio becomes larger compared to that of the two workers case because substitutes in each task become available. Under multitasking, $w_i = \lambda^2/8(1+\lambda^2 k), i = 1,2,3,4$ and $\pi_M = \lambda^2/2(1+\lambda^2 k)$. Thus, the ratio R_M of the profit to total wage bill remains one. As in the two-worker case, $R_S < R_M$ reflects that workers under single-tasking still have more bargaining power than under multitasking. Workers under single-tasking can exert negative externality on other workers, whereas workers under multitasking cannot affect the production more than their own investment. The following table summarizes results from this conjecture.

Table 2.3. Single-tasking vs. multitasking: four-worker case

	Single-tasking *S*	Multitasking *M*
Worker's Investment on Each Task	$(19/60)\lambda^2$	$\lambda^2/4(1+\lambda^2 k)$
Worker's Total Investment ($a_1 + b_1$ and $a_2 + b_2$)	$(19/60)\lambda^2$	$\lambda^2/2(1+\lambda^2 k)$
Production/Revenue	$P_S = (19/30)\lambda^2$	$P_M = \lambda^2/(1+\lambda^2 k)$
Profit	$\pi_S = (11/15)(19/60)\lambda^2$	$\pi_M = \lambda^2/2(1+\lambda^2 k)$
Wage	$w_S = (19/60)^2 \lambda^2$	$w_M = \lambda^2/8(1+\lambda^2 k)$
Ratio of Profit to Total Wage Bill	$R_S = 11/19$	$R_M = 1$

2.6.2. Existence of the External Labor Market

If workers need to make task-specific investments on tasks before production occurs, and the investments are useless outside a firm, the external labor market does not affect the previous results. This paper assumes that production requires skills, best practice of performing a task and physical labor. If workers need to search for and learn information to develop their private "work manual" for a task before production, a firm cannot replace internal workers with external ones even if they are identical in terms of skills (i.e., they have the same λ and k).

Suppose that one firm is hiring two workers and that there is an external labor market in which many identical workers are willing to work for the firm. Even in this case, the requirement of task-specific investment before production can insulate internal workers from the external labor market. The existence of "utility man" in Ford's mass production system provides a case in point. Ford reorganized the production process with extreme division of labor and extensively used unskilled workers. The system "needed a large group of utility workers on hand to fill in those employees who didn't show up each morning." (Womack, Jones and Roos 1990). According to Raff (1988), "substitutes were kept constantly on hand, at the factory's expense, to meet all emergencies." Even though the system could significantly reduce the amount of training on production workers (Raff and Summers 1986) and Ford's company faced a huge excess supply of unskilled workers, Ford's factories maintained the utility men to seamlessly utilize capitals and labor.

In addition, the existence of utility men mirrors the source of bargaining power that production workers have under specialization: The firm needed to maintain redundant workers due to the division of complementary production. By adopting multitasking, a firm can reduce bargaining power from the division of production. Osterman observed that contingent employment is negatively associated with such high performance work organization practices such as job rotation and quality circle (Osterman 2000).

2.7. Extensions

2.7.1. Contractible Production Method

The contractible production method reflects small-scale changes in human resource management practices. For example, a manager can negotiate with workers to introduce job rotation and other multitasking work practices. Workers face fewer liquidity constraints. In this case, this paper assumes that a manager and workers do not have liquidity constraints; therefore, either party can propose an alternative method and side payment. Because the change in practices does not seem to incur huge fixed costs, this paper assumes that fixed costs of both methods are the same and that the differential F is zero.

When a manager and workers can contract on a production method at date 0, an equilibrium production method depends on a worker's skill composition -- whether he has a high efficiency parameter (specialist) or a low cost of flexibility (generalist). Because a manager and workers do not have wealth constraints, if an initial production method does not maximize the total surplus, either party can propose an alternative production method and side payments to make them better off. A manager chooses a production method by comparing ex-ante total payoffs

$$TS(e_1^*, e_2^* \mid S) = P_S(e_1^*, e_2^*) - g_1(e_1^* \mid S) - g_2(e_2^* \mid S)$$

$$TS(e_1^*, e_2^* \mid M) = P_M(e_1^*, e_2^*) - g_1(e_1^* \mid M) - g(e_2^* \mid M)$$

PROPOSITION 4. *If $\lambda^2 k \geq 11/16$ (i.e., workers are more efficient at performing a single task), single-tasking is an equilibrium production method. If $\lambda^2 k < 11/16$ (i.e., workers are more efficient at performing multiple tasks), multitasking is an equilibrium production method.*

PROOF. See Appendix A. □

Proposition 4 shows that single-tasking can be equilibrium even if there are no financial constraints of workers and the fixed cost differential. Because the multitasking method is the first best production method, this result demonstrates how productivity gains due to the bargaining power shift in single-tasking affects our equilibrium outcome in the second best world. Workers' strong bargaining power in single tasking can lead to higher level of task-specific investments; whereas workers' weak bargaining power in multitasking can lead to lower investments in tasks. Thus, total surplus in single-tasking can be bigger than that in multitasking. The outcome depends on the type of workers. Suppose that workers are more efficient at performing a single task (specialists) and that an initial production method is multitasking. If so, workers will propose single-tasking and are willing to pay side payments to a manager. The gains in workers' surplus will be huge because of high productive efficiency and high bargaining power under single-tasking. Thus, workers are willing to compensate a manager's profit loss. Conversely, suppose that workers are more efficient at performing multiple tasks (generalists) and that an initial production method is single-tasking. If so, a manger will propose multitasking and side payments to workers because the manager's gains are large enough to compensate workers' possible loss.

Rajan and Zingales (1998) address a similar analysis of the hold-up power of employees and its effect on the division of labor. According to the authors, if workers' investments are complementary, granting multiple workers access to machines (i.e., single-tasking) will reduce the level of specific investment because workers have too much hold-up power against a manager. Instead, they show that one worker should be granted access to all machines (i.e., multitasking). Their result depends on the assumptions that a worker does not incur additional cost when he invests in multiple tasks (i.e., $k = 0$) and does not consider a worker's efficiency λ^2 when he can concentrate on a single task. As the proposition shows, even if under the extreme complementary Leontief case, workers' hold-up power can lead to productivity gains. The separation of complementary tasks can be sources of productivity as well as of hold-up of employees if workers are specialists.

2.7.2. Parallel Increase in the Relative Supply of More Educated Workers and Schooling Premium

Suppose that more education enhances workers' general skill and thus reduces the cost of worker's flexibility. Consider an economy that consists of two types of workers -- those with high education ("high type" with k_H) and those with low education ("low type" with k_L). The costs of flexibility are such that $k_H < k_L$ with $\lambda^2 k_L < 1/8$. Let's assume that firms employ high type workers always with the multitasking method and that firms employ low type workers always with the single-tasking method for a given fixed cost differential. Suppose that the portion of high type workers in an economy has increased due to education policy. The portion of firms that switch from single-tasking to multitasking begins to increase in the economy.

Because high type workers are flexible enough such that $\lambda^2 k_H < 1/8$, wages under multitasking are higher than under single-tasking. Therefore, the transition expands the number of workers who earn higher wages. Moreover, if education can reduce k_H, the wages can increase. Thus, schooling premium can be sustained with the increase in the relative supply of more educated workers through the expansion of the multitasking sector relative to single-tasking sector because workers in the multitasking sector can earn higher wages. Acemoglu (1999) came to a similar conclusion regarding the relation between the relative supply of educated workers and wage differential change.

2.7.3. Frequency and Size of Layoff

A production method can influence the frequency and size of layoff: Layoff becomes less frequent and its size becomes larger under single-tasking than under multitasking. The manger under single-tasking cannot finely adjust the number of workers to the change of the market demand because the dislocation of one worker has a negative external effect on production. When the demand of the product becomes low enough, a manager has to lay off workers across all tasks. Because one worker performs one task under single-tasking, the manager may need to lay off at least two workers for one unit decrease in the demand, whereas under multitasking, the manger may need to lay off only one worker for one unit excess supply.

Example. Suppose that the firm cannot hire or substitute an external worker for its internal worker in the production stage, but can fire its internal workers. Let's assume the demand for this product is in the range of $[3/10, 19/15]$ and that $\lambda^2 = 2$ and $k = 1/3$. Suppose that the fixed cost differential is zero. Also suppose that the manager lays off workers if and only if the demand is below their revenue. Their revenue levels and the number of workers inside the firm, which is based on the conjecture in section 2.6.1, are as follows:

Table 2.4. An Example of Frequency and Size of Layoff

Number of workers (n)	Revenue P_S under the Single-tasking	Revenue P_M under the Multitasking
4	19/15	12/10
3	2/3	9/10
2	2/3	6/10
1	0	3/10

If the demand decreases from $19/15$ to $3/10$, the manager under single-tasking lays off workers twice: once when demand reduces below $19/15$ and the other when demand reduces below $2/3$. A firm lays off two workers whenever it needs to lay off workers. For example, when the demand becomes below $19/15$, a firm will dislocate two workers because the production with three workers is the same as with two workers, and it does not need one “redundant” worker. The firm will maintain two workers until the demand reduces below $2/3$. If the demand is below $2/3$, then the firm folds its business. In the case of multitasking, with the same change in the demand, the manger lays off workers four times; a firm lays off one worker whenever it needs to lay off workers because there will not be any “redundant” workers even if one worker is dislocated.

2.8. Conclusion

This study examines how a firm's decision regarding the division of labor can influence compensation of workers with the same skill sets and the distribution of earnings between management and workers in a non-union setting. Specifically, this paper shows (a) that specialist-type workers earn more under single-tasking and generalist-type workers earn more under multitasking, (b) that the shift from single-tasking to multitasking can widen the earnings gap between management and workers, and (c) that technological progress, which facilitates multitasking, always widens the earning gap if workers are specialists. The main competing forces in the model are productive investment and the bargaining power that a production method determines.

This study has management implications. When a firm selects its production method, it should carefully consider the type of internal workers and choose the right combination. For example, if a firm's workers tend to be generalists, the firm can increase its profit as well as workers' wages by efficiently adopting multitasking. If a firm's workers tend to be specialists, enforcing multitasking may not be sustainable because it reduces workers' compensation and widens the earnings gap between management and workers. The results also indicate that firms should carefully evaluate types of technological change before it adopts a technology. If the technology is not well suited to the production method and the type of worker it hires, then the firm might not be able to maintain sustainable profit.

The relationship among the division of labor, compensation and technological progress that this paper examines provides policy implications as well. When setting the direction of education policy, policy makers should consider the type of technological change that society is facing. If our society is facing multitasking-biased technological change, workers need to be trained as generalists. By doing so, we have the opportunity to increase both wages and profit. But if workers are trained mainly as specialists, their wages will decrease and the earnings gap will further widen.

This study can be further extended. First, we can examine the relationship in an explicit dynamic setting. It will be especially interesting to note how workers' outside options change depending on their experience as a specialist vs. a generalist in a firm and the external labor market conditions. The analysis of the outside option requires dynamic approach. Second, we can incorporate workers' choice of skill composition and firms' hiring decisions into the current model. This extension can provide a more general framework for analyzing the effect of production method. Third, we can explore the effect of production method in a large firm setting. Especially, production method can change communication costs inside a firm. For example, workers in single-tasking may not be able to communicate with each other because they are performing different tasks. However, workers in multitasking can communicate better because they are more likely to understand his partner's tasks. In this case, the communication cost can be another factor that a manager needs to consider when she chooses production method. Lastly, we can test the predictions of this study regarding the distribution of earnings within a firm. The re-examination of inter-industry wage differentials literature (Dickens and

Katz 1986; Krueger and Summers 1988; Groshen 1991) in terms of the production methods across industries will be a novel way of approaching this topic.

CHAPTER 3

How does the management of research impact the disclosure of knowledge? Evidence from scientific publications and patenting behavior

3.1. Introduction

How economic institutions influence the production and distribution of knowledge has been one of the fundamental issues in economics. Since the seminal works of Nelson (1959) and Arrow (1962), economists have analyzed research and development activities in terms of the role of knowledge as a public good and the insufficient production of knowledge thereof (Dasgupta and David 1987). In particular, researchers have highlighted intellectual property rights such as patent to address the issue of incentive as it relates to the appropriation of the commercial value of knowledge, thus providing enough incentive to produce knowledge.

According to this view, researchers should claim the ownership of knowledge using appropriate intellectual property rights such as publication and patent (Dasgupta and David 1987). Dasgupta and David (1987, 1994) also distinguish between open "science" and proprietary "technology" and analyze different supporting institutions for two type of knowledge: While science is associated with a full disclosure supported by the rule of priority, technology is associated with restrictions on the use of knowledge and even secrecy (Merton

1973; Dasgupta and David 1994). But how do scientists choose these different types of intellectual property rights?

Researchers have already provided some answers to this question: Scientists choose certain types of intellectual property rights because of individual preferences for open science (Dasgupta and David 1994; Merton 1973; Stern 2004). Stern (2004) recently provides empirical evidence that scientists are willing to accept lower wage offer to participate in science activities because of their preference for knowledge production and diffusion for its own sake. However, as Dasgupta and David (1994) mention, "within the course of a day" the same researcher may participate in both realms – "open science" and "proprietary research." Moreover, most scientists work for universities or non-academic institutions. Can organizational factors influence the decision of scientists to participate in science or technology? We need to approach the issues of knowledge disclosure from an organizational perspective, because researchers are given different degrees of research discretion to participate in both regimes depending on the type of organization they work for.

This paper examines how control over research discretion within a research organization impacts the disclosure of scientific findings during a cumulative research stream. The paper develops a simple model to show how the presence of a directing manager affects a researcher's decision to publish or patent: Researchers tend to disclose their findings in the form of patent application under the manager even if they would prefer to publish. To estimate this effect of management on knowledge disclosure, this paper formalizes the insight that researchers under a manager's direction respond to a certain scientific discovery differently from researchers who have autonomy, provided that this discovery gives the manager an incentive to protect subsequent scientific findings.

Researchers have two alternatives in how they disclose their findings: They can publish or patent and have positive utilities from successful publication and patent. The probability of getting their discovery published does not depend on whether their contents are "basic" or "application." However, the probability of getting a patent on their discovery increases as the contents become more applied, because a patent law explicitly requires "utility." Therefore, a researcher's optimal disclosure decision is to publish the basic knowledge and patent the "sufficiently" applied knowledge because patent is more likely to be granted to the application-oriented knowledge.

The presence of the directing manager can affect the optimal strategy of a researcher when managers have different preferences for patents from researchers and maintain the final decision rights on researchers' disclosure. When a scientific discovery possesses a certain level of application potential, the manager does not want to publish the discovery without a protective measure. Because the manager has the final rights on the disclosure, the researcher's optimal strategy is affected as long as he works for the organization: If this researcher works for a research organization in which a manager controls the disclosure of findings from her organization, the researcher's optimal decision will lean toward a more protective form of disclosure as research advances to the commercializable stage.

This effect of organization on knowledge disclosure can be identified because of the dual characteristics of scientific research and their influence on incentives (Stokes 1997; Mokyr 2002). Scientific research simultaneously pursues fundamental understanding and application, and the basic and applied findings provide different incentives to the manager and researcher. Their different incentives are coordinated through who has the final decision rights on how to disclose. However, previous empirical studies may have confused the effects of research management with the evolution of scientific knowledge on researchers' participation in science (i.e., publication) or technology (i.e., patent), because claiming intellectual property rights in the form of patent is not always feasible.

To separate the effect of the evolution of underlying knowledge in research from that of management of disclosure, this paper first considers a research path as *multiple discoveries associated with a single human gene*, and uses the specificity of individual genes to control for the heterogeneity of research paths. The rationale is that multiple discoveries associated with the same gene are closely connected through their focus on the same biochemical material. Moreover, this paper uses the dates of publications of the gene's linkage to a disease to identify a shift from the basic and applied research stages in human gene research. Although human genes are not necessarily related to diseases, a discovery that a gene can cause a disease sparks intensive research for commercialization in the subsequent research path.

Building on this control for the heterogeneous paths of knowledge and the shift from the basic to applied stage, this paper exploits the observation that the control rights over the disclosure of research findings differ between academic ("unmanaged") and non-academic ("managed") research organizations and estimates the effect of organizational variation. With these carefully defined variables, a differences-in-differences analysis before and after the discovery of the disease linkage across the two types of research organization can show the effect of control rights over research discretion on knowledge disclosure over time.

The results provide broad support for the predictions of a control rights theory of disclosure. First, managed research organizations induce researchers to shift from open science to proprietary research more than universities do when they recognize the advantage of the applied stage during research. Second, researchers in biotech and pharmaceutical firms tend to reduce the number of their publications to protect their findings, compared to the number of publications produced by university researchers in the applied stage. This implies that private organizations tend to be more secretive in the applied stage. Third, non-academic public research organizations also increase their protection of scientific findings, especially by patent applications, compared to universities. Finally, these effects of management are the strongest in the middle of the applied stage: In the case of biotech firms, the magnitude of publication reduction was the largest around the 15th and 20th years of the applied stage. In the case of non-academic public research organizations, the magnitude of patent increase was the largest around the 5th and 10th years of the applied stage.

This paper contributes to the literature by (a) estimating the effect of organization on the disclosure of scientific findings in terms of publication and patent in human gene research, (b) systematically analyzing research organizations beyond the traditional distinction between industry and university to include non-academic public research organizations and (c) suggesting an effective control variable to address the heterogeneity of scientific research projects.

The paper is organized as follows: Sections 3.2 and 3.3 examine literature review and a motivating example of the "BRCA" gene research. Sections 3.4 and 3.5 suggest a simple theoretical framework, as well as an empirical strategy for testing the theory's implications.

Sections 3.6 and 3.7 discuss the data set and present empirical results. Section 3.8 offers concluding remarks.

3.2. Literature Review

The interaction among science, innovation and economic institutions has drawn considerable attention in economics research. In addition to their practical implications for modern economies (Kuznets 1966), the unusual characteristics of science and innovation have captivated economists. Nearly 50 years ago, Nelson (1959) and Arrow (1962) viewed the issue in terms of tension between incentives to produce knowledge and incentives to disseminate knowledge based on the property of public good. Since then, economists have focused mainly on analyzing and designing efficient institutions to address the public-good nature of scientific knowledge and innovation based on property rights. The designs of economic institutions strive primarily to solve the "incentive dilemma" in producing and disseminating scientific knowledge and innovations. Recently, the cumulative nature of knowledge and innovations (i.e., old knowledge and innovations spawn new knowledge and innovations) has been analyzed formally from the traditional perspective (Gallini and Scotchmer 2003; Scotchmer 1991, 1996, 2004). As a solution to the incentive dilemma in a cumulative-innovation setting, Scotchmer (1996) suggests broad patent protection with exclusive licensing on upstream, basic innovations. On the other hand, the anti-commons literature insists that property rights on cumulative knowledge can restrict the use of knowledge because they create too many fragmented rights on a single product or stack license fees on downstream innovations (Heller 1998; Heller and Eisenberg 1998). The literature on knowledge and institutions is insightful, but it implicitly assumes no hierarchy among owners of rights (Heller 1998).

Although these studies provide insight into the understanding of technological innovation and economic institutions, the resource allocation mechanism in science, another backbone of modern economic development, has less been examined (Dasgupta and David 1987). In their seminal paper, Dasgupta and David (1994) illustrated the two research regimes – science and technology – and examined reward structures, rules and norms that support these regimes. More specifically, they suggest that different reward structures lead to different disclosures of research findings: The rule of priority in science encourages a full disclosure, whereas the appropriation of rent in technology encourages partial disclosure or secrecy. However, the public-good approach to research and Dasgupta and David's "new" economics of science do not explicitly examine the role of organization in scientific research. There needs to be a systematic examination of research organization to allow scientific researchers to participate in both regimes simultaneously.

Recent studies in the economics of organization do address organizations' role in the production and transfer of innovation using a control rights approach to organization. Aghion and Tirole (1994) argue that efficient investments in innovation through ownership structure are crucial in organizing a firm's research activity. Their model, however, considers innovation as a final product rather than a cumulative process. Aghion and Tirole (1997) also developed a theory of the allocation of formal and real authorities within an organization based on asymmetric information between a principal and an agent. They examined how a principal and agent's incentives to acquire information are affected by delegating formal authority to an agent and determined that the agent has increased incentive to acquire information. Based on authority consideration, Aghion, Dewatripont and Stein (2005) list creative control and directness in research activities as the key characteristics of public and private research organizations, and they explore the knowledge transfer between these organizations. Building on an empirical result illuminating wage differentials among researchers (Stern 2004), they show that public research organizations reap an economic advantage when they conduct early research, and that the knowledge transfer from a public to a private organization can be socially optimal over the course of a research project. Although the literature provides valuable explanation of organizations' role in knowledge production and transfer, it does not explicitly address how different types of knowledge affect organizational decisions.

As Stokes (1997) maintains, scientific research can have a dual characteristic. That is, a single discovery could serve the purpose of fundamental understating for applications. Other scholars also have clarified the characteristics of knowledge and/or knowledge-producing institutions (Dasgupta and David 1994; Foray 2004; Stephan 1996). Based on novel ideas regarding different types of useful knowledge and their access costs, Mokyr (2002) explains how knowledge changes can restrict or facilitate the development of institutions and human welfare.[4] This paper employs the idea that the change in the nature of knowledge can affect the behaviors of economic agents because the mode of disclosure depends on whether the nature of underlying knowledge is fundamental understanding or application in addition to the reward structure.

In addition to generating theoretical developments, recent literature has empirically investigated institutions' effect on knowledge accumulation. Studies have examined institutions

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[4] Precisely speaking, Mokyr insists on the coevolution of knowledge and institutions (Mokyr 2002).

ranging from biological research centers (Furman and Stern 2004) to universities (Jaffe, Trajtenberg and Henderson 1993; Henderson, Jaffe and Trajtenberg 1998; Branstetter 2001; Mowery et al. 2004) to patents (Murray and Stern 2005) to patent pools (Lerner and Tirole 2004) and finally to standard setting institutions (Rysman and Simcoe 2005).

Clearly, previous empirical studies have provided insightful findings regarding knowledge, organizations and institutions, but the literature does not effectively control for the unobserved heterogeneity of underlying knowledge on which these organizations and institutions rest. Some knowledge, for instance, might be especially difficult to transform into a marketable innovation. Moreover, many studies try to measure knowledge transfer using citations for publications or patents, but such citation analysis might weakly reflect the underlying connection between these knowledge products.[5] Therefore, this paper carefully chooses the unit of observation that can control the heterogeneity suggested in the studies of identical twin case (Ashenfelter and Krueger 1994) and vaccine industry case (Finkelstein 2004). Lastly, to measure disclosure of scientific findings, this paper simultaneously considers publication and patent because current literature suggests that patent is only a small portion of research outcomes and that patentable research is also publishable (Agrawal and Henderson 2002; Cohen, Nelson and Walsh 2000; Murray and Scott 2005).

Therefore, building up on the theoretical implication that researchers under different types of management will respond differently to the same shift from basic to applied knowledge, the task

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[5] Citations to prior patents in a patent document have legal consequences; thus, they might reflect closer relations between two patents than citations to publications in a paper between two papers. However, even in patent documents, citations to prior literature still have the same "noise."

of this paper is to examine the effect of research management on researchers' disclosure through publication or patent. In the subsequent section, the history of the breast and ovarian cancer (BRCA) gene research suggests that a researcher's organizational affiliation can affect such decision on the disclosure and production of knowledge.

3.3. BRCA Gene Research Case

The history of searching for the BRCA 1 gene -- the hereditary breast and ovarian cancer gene on chromosome number 17 -- and the subsequent development of commercial applications vividly show how researchers and organizations respond to scientific discoveries during a scientific project (Davies and White 1996; Williams-Jones 2002). At the 1990 American Society of Human Genetics Meeting, Mary-Claire King described the mapping of the gene responsible for some forms of familial breast cancer. King and her group traced the gene to one of twenty-three pairs of human chromosomes, i.e., chromosome number 17 (Davies and White 1996). Her discovery has revolutionized researchers' perspectives on how a single gene and breast cancer could be related, and sparked an intensive race to identify the "rogue" gene. Due to her discovery, as Davies and White point out (1996, 101), "a project that had seemed so complex that it had frightened off most of the top geneticists around the world did not look so hard anymore." The gene was finally identified by Mark Skolnick and 44 other scientists in 1994. Their organizational affiliations were diverse: University of Utah, McGill University, Eli Lilly, Myriad Genetics and the National Institute of Environmental Health Science (Davies and White 1996).

After the identification of the BRCA 1 gene, further research studies were conducted and applications such as diagnostics were developed by researchers in various organizations. The results were either published or patented. According to PubMed, a bibliographical database of the National Institute of Health, 325 scientific articles were published on the BRCA 1 gene as of November 2005. Among these, 318 papers were published after the gene was identified. Patents involve mutations in the BRCA 1 gene; the use of the mutations for diagnosis and prognosis for breast and ovarian cancer; and the development of therapeutics (Williams-Jones 2002). Nineteen patents on the BRCA 1 were applied for after 1995 (Jensen and Murray 2005; USPTO). Research organizations that conducted subsequent research and development were also diverse: universities (e.g., University of California, University of Utah, University of Washington, Vanderbilt University), biotech startups (e.g., Myriad Genetics, OncoMed, Gene Logic), research institutions (e.g., Fox Chase Cancer Center, Cancer Institute) and the US government, among others.

This BRCA gene stimulates questions as to how researchers decide the disclosure of scientific findings in different organizations: If Mary-Claire King was not at UC Berkeley but at a private firm, could she have publicly shared her findings if her manager wanted to obtain patents on this gene after completing its identification? How would we expect King's disclosure decision to be affected due to her organizational affiliation? To systematically analyze this question, this paper develops a simple model on how the existence of management affects the researchers' decisions on knowledge disclosure.

3.4. Model

This section examines how the management of research can impact researchers' choice of participating in open science and proprietary research by publishing and patenting their discoveries. This paper regards (a) the presence of a manager (b) a manager's decision rights on researchers' disclosure and (c) the procedure that requires the researcher to consult before he dispatches his findings for journal submission or patent application as conditions that differentiate types of organizations. The analysis starts with a benchmark case - unmanaged-research case – in which researchers have final decision rights on how to disclose. After deriving the researcher's optimal strategy under an unmanaged-research type of research organization such as a university, the controlling manager and other conditions are introduced to examine how the optimal strategy of the researcher will be affected under this managed-research type of organization.

3.4.1. Benchmark Case: unmanaged-research type of organization

The research stage ϕ is a point on a real line [0, 1]. 0 implies that it will take an infinite amount of time to commercialize research; 1 implies that the research result can be commercialized immediately. Thus, the larger ϕ implies that research is in the more applied stage in the sense of commercialization. A researcher can disclose scientific findings at a research stage ϕ in journal submission or in patent application. In doing so, he incurs fixed costs I_{pub} and I_{pat}, respectively. If he submits his findings to a journal, a peer review procedure will be initiated. After the review procedure, the submission will be accepted with a probability $p(\phi)$, and these findings will be fully disclosed to the public. Moreover, the public can commercialize these findings without permission from the researcher. The researcher will have his utility b_{pub} from his publication, but 0 if his submission is not accepted. This paper assumes that $p(\phi) = p$ because the peer review procedure does not depend on whether its content is basic or applied.[6] If scientific findings are submitted for patent, the patent office initiates the review process and issues a patent with probability $q(\phi)$. After the patent is issued, the public can assess and evaluate these findings; only with permission from the researcher, they can commercialize these findings. Thus, the patent grant provides the researcher with a monetary opportunity. If the patent is granted, he will get his utility b_{pat} and 0 otherwise. Because the patent-related laws require "utility" for patentability, this paper assumes the following: $q(0) = 0, q^{'}(\phi) > 0$ for all ϕ, and $q^{''} \geq 0$. The researcher's expected payoff from journal submission and patent application are $pb_{pub} - I_{pub}$ and $q(\phi)b_{pat} - I_{pat}$, respectively. The researcher's strategy s_{res} is a function such that $s_{res} : [0,1] \rightarrow \{\text{ submit, apply }\}$. In this setting, the researcher's optimal strategy is a cutoff strategy: He will submit his findings to a journal if the research stage is sufficiently basic and will apply for a patent otherwise.

PROPOSITION 5. *There exists a research stage* $\phi_{no} \in [0,1]$ *such that a researcher submits scientific findings to a journal for publication if* $\phi \leq \phi_{no}$ *and applies for a patent otherwise.*

PROOF. See Appendix B. □

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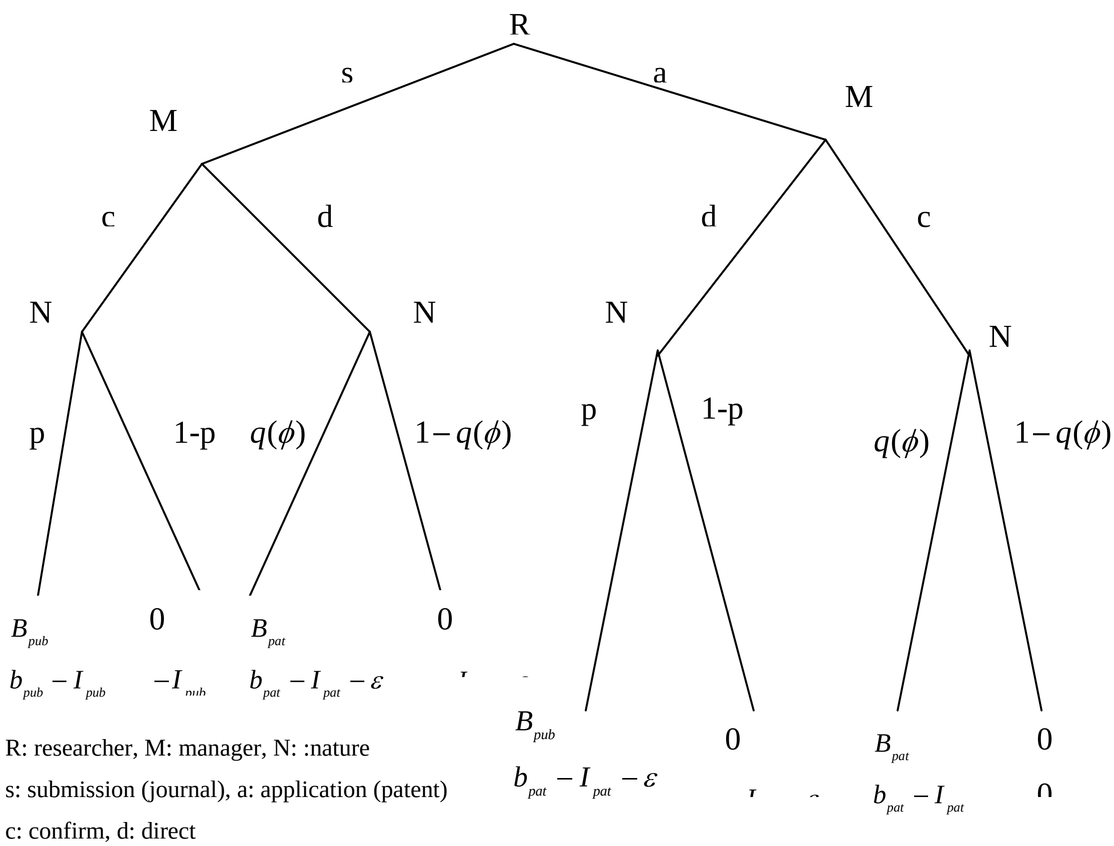
[6] $p(\phi)$ can be a decreasing function because an immediately commercializable knowledge may not be accepted by a scholastic journal. However, a decreasing $p(\phi)$ does not affect the results.

3.4.2. Effect of the control rights over disclosure: managed-research type of organization

This paper refers to a managed-research-type organization as (a) the presence of a manager with an objective function different from that of a researcher, (b) the manager's final decision rights on researchers' disclosure and (c) a procedure that requires the researcher to consult the manager before he dispatches his submission or patent application. In other words, the controlling manager can agree or change researchers' decisions. This paper assumes that a manager confirms or asks for changes. For example, if the researcher consults with the manager before his journal submission, the manager confirms the submission or directs the researcher to apply for a patent. Thus, the manager's action set is $\{\text{confirm}, \text{direct}\}$. The manager has her utility B_{pub} from the researcher's publication and B_{pat} from the patent grant. If the researcher is directed to change what he consulted on, he incurs an infinitesimally small amount of cost $\varepsilon > 0$ because he has to modify his preparations or resents being directed. This paper assumes complete information between the manager and researcher on $\phi, p,$ and $q(\phi)$. In this type of research organization, the manager and researcher play a simple game. First, given ϕ, the researcher decides how to disclose and then consults the manager. After being consulted, the manager decides whether to confirm or instruct the researcher to change his disclosure. If the manager confirms, the researcher's decision will be implemented. If she directs him to change his method of disclosure, he must do as directed and implement the changed decision. Lastly, the submission is evaluated by the peer review procedure and the patent application by the patent review procedure, and the final results are issued. The game ends.

Figure 3.1. Sequences of the game

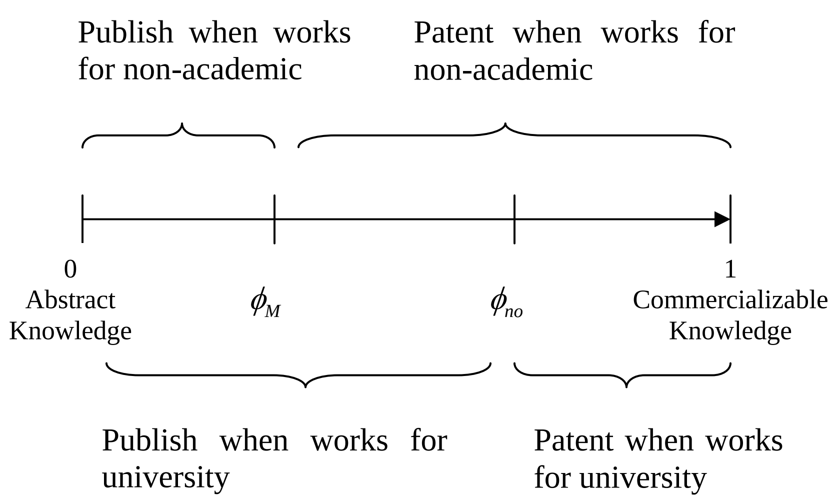


PROPOSITION 6. *(a) At equilibrium, there exists* $\phi_M \in (0,1)$ *such that the researcher tries to publish and the manager agrees if* $\phi \le \phi_M$ *; the researcher tries to patent and the manager agrees otherwise. (b) Suppose that* $I_{pat} = I_{pub}$. *Also suppose that the manager prefers patent to publication, while the researcher prefers publication over patent. Then,* $\phi_M < \phi_{no}$.

PROOF. See Appendix B. □

From these propositions, two comparative statistics can be obtained. First, in the sufficiently applied stage, if a researcher works for a managed-research-type organization, he is less likely to publish and more likely to patent. Proposition 2 suggests that in the range $\phi_{no} - \phi_M$ the researcher applies for a patent instead of publication even if he would like to publish. Second, the presence of a controlling manager is mostly effective in the middle of applied stages. In the early basic or the late applied stages (i.e., either $\phi << \phi_M$ or $\phi_{no} << \phi$), the researcher can maintain the same strategy as in the benchmark case, i.e., unmanaged-research type, because the manager and researcher are not in conflict over how to disclose in those stages. Thus, the decrease in publication and increase in patent because of the existence of management will be the strongest in the middle of applied stages. The following figure illustrates these propositions.

Figure 3.2. Impact of management on publication and patent



3.5. Empirical Framework

From the previous theory section, (a) researchers in the managed-research-type organization respond to the advance of applied stage with fewer publications and more patents than those in the unmanaged-research-type organization and (b) the effect of the existence of management will be the strongest in the middle of applied stage. To estimate these effects of the management of research findings on the disclosure pattern, we need to examine how the shift from unmanaged-research to managed-research type organization affects the number of publication and patent in the applied stage of a research path. However, the important issues for empirical test are (a) the heterogeneity of researchers' quality (b) the unobserved heterogeneity of research projects and (c) identifiable basic and applied stages in individual research projects.

The heterogeneity of researchers' quality can confound the effect of organization if researchers in a certain type of organization are significantly less able to produce abstract or commercializable knowledge. Human gene research offers a setting in which this issue can be addressed. In human gene research and biotechnology in general, researchers' qualities can be assumed to be homogenous across academic and non-academic organizations because virtually all researchers in this field have earned Ph.D. degrees, and they frequently switch their positions between academic and non-academic organizations. For example, many leading biotech firms such as Myriad were founded by university professors. In addition, human gene research, and biotechnology in general, are unique in the sense that researchers in academia and in industry share interests in the fundamental understanding of genes and their applications (Murray and Stern 2005).

The unobserved heterogeneity of research projects can also confound the effect of the management of research findings: Some results from research projects can be very hard to commercialize because they are fundamental but abstract. Conversely, research findings from some projects are more likely to be patented. Moreover, the likelihoods of publishing and patenting are also related to which stage (i.e., basic vs. applied) the research project is proceeding. If these are the case, the effect of management and types of underlying knowledge are confounded.

This paper controls for the heterogeneity of research paths by exploiting the observation that multiple discoveries are associated with a single research path through their interests in the common research material. In human gene research, we observe that researchers make new discoveries regarding a single human gene and that those multiple discoveries are closely connected through their focus on the same biochemical material. By regarding multiple discoveries on a single gene, we can construct reliable a research path and control for the unobserved heterogeneity of research paths.

To set identifiable basic and applied stages, this paper uses the observation that a certain discovery sparks intensive research for application in this research path. Specifically, publication of a gene's linkage to a disease can identify a shift from the basic to the applied research stages. We can predict that research following such discovery will be more focused on the commercialization aspect.

The disclosure of multiple discoveries of specific genes, however, requires additional effective controls for temporal aspects in scientific research, such as internal accumulation of knowledge in the research path and external changes in legal and social environments. Internal accumulation can affect the disclosure because research findings from the later stages of the research path are more likely to be patented. As an example of the effect of external changes, before the *Diamond v. Chakrabarty* case it would have been almost impossible to apply for a patent on manmade microbes. This paper, therefore, addresses two kinds of temporal effect: First, to manage the internal accumulation of knowledge in a given research path, this paper considers the number of years that have elapsed since the first publication or patent application on a specific gene (research age). Second, to address environmental changes (period), this paper considers periods defined by major events in biotechnology development (Stern and Loffler 2004).

In the first period, 1972 to 1980, fundamental technologies in biotechnology, such as the Cohen-Boyer method, were developed; the first biotechnology company, Genentech Inc., appeared; and the Supreme Court ruled in favor of the patent on manmade microbes (1980). In the second period, 1981 to 1988, patenting on living organisms became active: Plants could be patented in 1985, and a living mammal was patented in 1988. In the third period, 1989 to 1995, the potential for the commercial marketing of biotechnology seemed to increase. Also, the FDA announced that genetically engineered tomatoes were safe; BRCA 1, the breast cancer gene, was discovered; and the first full genetic sequence of a living organism, *Haemophilus Influenzae*, was completed. In the fourth period, 1996 to 2000, research on living organisms’ gene sequences were intensified, and the first draft of human genome sequence was completed (2000). In the last period, 2001 to 2004, the final sequence of the human genome was produced (2003), and research intensified on genome architecture across the spectrum of biodiversity (Burrill 2003, 17).

This paper assumes that the effect of age is constant within a period but varies across the periods, the key idea being that the same age might not generate the same effect on publication and patenting behavior in different environments. This paper models the "period varying" effect of age as follows:

$$
\begin{aligned}
AGE \text{ effect } &= \alpha_1 age \\
&+\alpha_2[age-(1980-first\_year\_in\_GENE)]*I_{[age\geq 1981-first\_year\_in\_gene]} \\
&+\alpha_3[age-(1988-first\_year\_in\_GENE)]*I_{[age\geq 1989-first\_year\_in\_gene]} \\
&+\alpha_4[age-(1995-first\_year\_in\_GENE)]*I_{[age\geq 1996-first\_year\_in\_gene]} \\
&+\alpha_5[age-(2000-first\_year\_in\_GENE)]*I_{[age\geq 2001-first\_year\_in\_gene]} \\
&= \alpha_1 age+\alpha_2[year-1980]*I_{[year\geq 1981]}+\alpha_3[year-1988]*I_{[year\geq 1989]} \\
&+\alpha_4[year-1995]*I_{[year\geq 1996]}+\alpha_5[year-2000]*I_{[year\geq 2001]}
\end{aligned}
\tag{1}
$$

, where *age* equals *year* minus *first_year_in_GENE*, *I* is an indicator variable, *first_year_in_GENE* is the year of the first publication/patent application regarding the specific gene and {1980, 1988, 1995, 2000} is a set of years demarcating each period in the data set. In other words, calendar years are transformed in terms of age and period adjustment $a_i[year-j]*I_{[year\geq j+1]}, i=2,3,4,5\ j=1980,1988,1995,2000$.

Using these control variables, this paper uses two dummy variables as independent variables: (a) a controlling manager dummy that is equal to one if publication (patent application) is generated by managed-research-type, i.e., non-academic, organizations, and (b) an applied stage dummy that equals to one if the year is later than the discovery of a disease-causing mutant of a gene. Because three kinds of a managed-research-type organization (i.e., biotech startups, pharmaceutical companies and other public organizations such as the NIH) are observed in human gene research, this paper simultaneously uses three pairs of data sets: biotech firms vs. universities, pharmaceuticals vs. universities and other public research organizations vs. universities. The purpose of simultaneously using these pairs is to confirm that common patterns are estimated from the unmanaged vs. managed research perspective rather than a specific type of organization such as biotech firms.

This paper defines as dependent variables the number of publications and patents on specific genes through the years by research organizations. Because a data set has a count data characteristic, negative binomial regression is adopted. To find common patterns of the effect of management in research, this paper implements the difference-in-difference analyses on each of three data sets: biotech firms vs. universities, pharmaceuticals vs. universities and public research organization vs. universities. The baseline regression equations are as follows:

$$\begin{aligned} Publication_{i,t,k} = f(&\phi_{pb,1}APPLIED + \phi_{pb,2}MANAGER + \phi_{pb,3}APPLIED*MANAGER \\ &+ \sum_{i=1}^{61}\alpha_{i,pb}d_i + \beta_{1,pb}AGE + \sum_{j=2}^{5}\beta_{j,pb}ADJUST_j;\varepsilon) \end{aligned} \tag{2}$$

$$\begin{aligned} Patent_{i,t,k} = f(&\phi_{pt,1}APPLIED + \phi_{pt,2}MANAGER + \phi_{pt,3}APPLIED*MANAGER \\ &+ \sum_{i=1}^{61}\alpha_{i,pt}d_i + \beta_{1,pt}AGE + \sum_{j=2}^{5}\beta_{j,pt}ADJUST_j;\varepsilon) \end{aligned} \tag{3}$$

$i: gene\ id,\ t: year,\ k: organization$

, where $\phi_{pb,1}$, $\phi_{pt,1}$ are the fixed effects of being in the applied stage; $\phi_{pb,2}$, $\phi_{pt,2}$ are the fixed effects of the presence of the controlling manager ; $\phi_{pb,3}$, $\phi_{pt,3}$ are the effects of the manager's presence in the applied stage; the $\alpha_{i,pt}$ and $\alpha_{i,pb}$ are gene fixed effects; d_i is a dummy for a gene *i*

= 1,…,61; $\beta_{1,pt}$ and $\beta_{1,pb}$ are baseline effects of age; and $\beta_{j,pt}$ and $\beta_{j,pb}$, $j = 2,3,4,5$ are age effects adjustment in a period *j*.

To test the second proposition that the effect of management is the strongest in the middle of the applied stage, this paper examines how the effects change over various time windows in the applied stage. To test the dynamic effects of the organization, this paper analyzes the coefficient of interaction terms in terms of multiple time windows of the applied stage. The regressions using a time window are as follows:

$$Publication_{i,t,k} = f(\phi_{pb,1}APPLIED + \phi_{pb,2}MANAGER + \sum_{h=1}^{n_j}\phi_{pb,h}APPLIED * MANAGER + \sum_{i=1}^{61}\alpha_{i,pb}d_i + \beta_{1,pb}AGE + \sum_{j=2}^{5}\beta_{j,pb}ADJUST_j; \varepsilon) \quad (4)$$

$$Patent_{i,t,k} = f(\phi_{pt,1}APPLIED + \phi_{pt,2}MANAGER + \sum_{h=1}^{n_j}\phi_{pt,h}APPLIED * MANAGER + \sum_{i=1}^{61}\alpha_{i,pt}d_i + \beta_{1,pt}AGE + \sum_{j=2}^{5}\beta_{j,pt}ADJUST_j; \varepsilon) \quad (5)$$

$i: gene\ id,\ t: year,\ k: organization$

, where $\phi_{pt,h}, \phi_{pb,h}$ is the dynamic effect of the managed-research organization at *h*th window. Each window consists of the same number of years except for the last window. For example, each window consists of five years.

3.6. DATA

3.6.1. Data construction and sources

To test the implications of previous sections, this paper constructs a data set from human gene research that addresses the following tasks: (a) identifying a research path and measuring the disclosure of scientific findings in the research path in terms of publication and patent (b) measuring the time of a disease-causing gene mutant discovery that can subsequently spark intensive research for applications (c) recording whether a research organization in the research path is managed-research type and (d) constructing the research age and adjustment for periods.

To construct a research path variable, this paper uses gene-related databases' procedure of managing information, which issues an identification number for each human disease gene. Two databases are explored: the Entrez Gene database of the National Center for Biotechnology Information (NCBI), a division of the National Library of Medicine (NLM) at the National Institutes of Health (NIH), and the Online Mendelian Inheritance in Man (OMIM) database of the McKusick-Nathans Institute for Genetic Medicine at Johns Hopkins University. Entrez Gene is a database of gene-specific information[7] that integrates various kinds of research on genes[8] and

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[7] For a description of the Entrez Gene database, see Maglott et al. (2005) and www.ncbi.nlm.nih.gov.

[8] The Entrez Gene database maintains "nomenclature, chromosomal localization, gene products and their attributes, associated markers, phenotypes, interactions and a wealth of links to citations, sequences, variation details, maps, expression reports, homologs, protein domain content and external databases" (Maglott et al. 2005).

provides a unique integer identifier (i.e., a "gene id") for each gene. This gene id can represent comprehensive research studies on a specific gene. Thus, identifying the research path in this way can account for the heterogeneity of knowledge underlying research paths.

As of October 2005, the Entrez gene database contained 32,786 human genes, but not all of these genes are related to human diseases. To focus on human disease genes, this paper refers to the OMIM database. The OMIM database[9] is an online catalogue of human genes and genetic disorders based on *Mendelian Inheritance in Man* (McKusick 1998). Because Johns Hopkins University and NCBI manage the OMIM, it can be cross-referenced to Entrez Gene. As of October 5, 2005, among 16,286 human disease-related genes, OMIM featured 390 human genes with known sequences and phenotypes. These 390 genes, therefore, can serve as candidates for research projects.

From these identified research projects, this paper counts the publications and patents produced under each gene id. The Entrez Gene database collects publications on a gene and categorizes them under gene ids by using its internally developed filter and PubMed, a bibliographic database of NCBI. Therefore, the number of publications pertaining to a gene is available. To count the patents under each gene id, this paper employs a subset of data developed by Jensen and Murray (2005). Using NCBI's BLAST software, they compare sequences of all genes featured in the databases of NCBI and of USPTO and then map patents onto gene ids.[10] According to a subset of their data, 163 gene ids carry at least one patent. To homogenize genes in terms of the composition of basic and applied knowledge, this paper selects

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[9] For a description of the OMIM database, see Maglott et al. (2002) and www.ncbi.nlm.nih.gov/Omim.

[10] For a detailed description of this procedure, see Jensen and Murray (2005).

61 genes that have at least three patents and at most 100 publications.[11] In this sense, the data set is not a random sample, which might lead to overstating the patent decision.

To tackle the second task, measuring when the focus of research begins to shift toward commercialization in human gene research, this paper uses the date of the first publication regarding an allelic variant of a gene from the OMIM database. According to OMIM, most allelic variants represent disease-producing mutants. The discovery of the allelic variant, therefore, can be regarded for two reasons as the unexpected shift that can spark intensive research for applications.[12] First, as mentioned earlier, genes are not inherently disease related: They are biochemical materials carrying hereditary and biological information. Thus, not all genes are reported to have allelic variants. Second, only a few human disease genes are known for their sequences and phenotypes as of October 2005. Thus, under the current circumstances, discoveries of allelic variants can be regarded as unexpected. In this paper's data set, allelic variants of nine out of 61 genes have yet to be reported.

This paper records universities as the unmanaged-research type, and non-academic organizations as the managed-research type. In addition, three kinds of managed-research-type organizations are observed in human gene research: biotech startups, pharmaceuticals and other public research organizations. Other public research organizations comprise hospitals, independent research institutes and governments. The categorization of biotech and pharmaceutical companies mainly draws from the RecapIP database, an established private

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[11] In the subset, three out of 61 have only known sequences without known phenotypes.

[12] A curator of OMIM also confirms that the discovery of allelic variants can reflect the change of knowledge on genes.

database providing information on the biotechnology industry. The categorization of other public research organizations stems from various sources, including companies' Web sites.

Two issues stand out in the categorization procedure. First, multiple authors per publication and multiple assignees per patent must be considered. For publications, this paper analyzes the organizations affiliated with the first author, because the PubMed database provides institutional affiliations only for first authors. For patents, each of the assignees' organizations is counted as one organization and categorized separately. Second, a publication's first author can be affiliated with multiple organizations. For example, an author from a university often is affiliated with a hospital, research institute or government institution. In these cases, universities are considered the primary organization because they tend to allow researchers to be affiliated with other organizations, whereas other organizations usually do not permit multiple affiliations.

The last task is to construct the age variable and adjustment terms for periods. To construct age variable, this paper calculates the number of elapsed years since the first publication or patent application in each gene id; this variable is labeled AGE. To reflect external changes in scientific, economic and legal environments, this paper groups calendar years into five periods, which are designed to reflect salient environmental changes in biotechnology history (Stern and Loffler 2004). As discussed in the previous section, the effect of age is modified depending on the period in which the gene research is being implemented.

Table 3.1. Biotechnology Timeline after 1972

Period	Year	Key Player	Event
Period 1: 1972 - 1980	1972	Paul Berg	Cut sections of viral DNA and bacterial DNA with same restriction enzyme
			Spliced viral DNA into bacterial DNA
	1973	Stanley Cohen	First recombinant DNA organism produced
		Herbert Boyer	Genetic engineering begun
	1975		Moratorium on recombinant DNA techniques
	1976		National Institutes of Health guidelines developed for study of recombinant DNA
	1977		First practical application of genetic engineering
	1978	Genentech, Inc.	Genetic engineering techniques used to produce human insulin in E.coli
			First biotech company on NYSE
		Stanford University	First successful transplantation of mammalian gene
			Discoverers of restriction enzymes receive Nobel Prize in medicine
	1979	Genentech, Inc.	Human growth hormone produced and two kinds of interferon DNA from malignant cells transformed a strain of cultured mouse cells – new tool for analyzing cancer genes
	1980		U.S. Supreme Court decided that manmade microbes could be patented
Period 2: 1981 - 1988	1983	Genentech, Inc.	Eli Lilly licensed to make insulin
			First transfer of foreign gene in plants
	1985		Plants became patentable
	1986		First field trials of DNA recombinant plants resistant to insects, viruses, bacteria
	1988		First living mammal patented
Period 3: 1989 - 1995	1993		Flavr savr tomatoes sold to public
	1994		FDA announced that Flavr savr tomatoes are as safe as those bred conventionally
			BRCA 1, the first breast cancer susceptibility gene, was discovered
	1995		The first full gene sequence of a living organism was completed for the bacterium *Haemophilus influenzae*.
Period 4: 1996 - 2000	2000		First draft of human genome sequence completed
Period 5: 2001 - 2004	2003		Final sequence of the human genome produced

Source: Stern and Loffler (2004)

3.6.2. Summary statistics

Tables 3.2 and 3.3 show the definition of variables and summary statistics, respectively. The complete dataset comprises a publication dataset and a patent dataset from each gene id for each of three managed vs. unmanaged-research pairs. A research path is recorded as starting in the first publication year or the first patent application year, depending on which is earliest. The earliest year is 1972. Research results are recorded until 2004. The total number of gene ids is 61, the total number of publications is 2,721 and the total number of patents is 398. The number of observations in gene id-year pair is 1,167 for each of the following kinds of organization: biotech firms, pharmaceuticals, other public research organizations and universities.

Table 3.2. Variable Definitions

Variable	Definition	Source
Dependent Variables		
$BIO\_PUBLICATION_{ik}$	# of publications by biotechnology companies on gene *i* in year *t*	Entrez Gene; PubMed; author verification
BIO_PATENT_{it}	# of patents by biotechnology companies on gene *i* in year *t*	Jensen and Murray; USPTO; author verification
$PHARMA\_PUBLICATION_{it}$	# of publications by for-profit, non-biotechnology organizations on gene *i* in year *t*	Entrez Gene; PubMed; author verification
$PHARMA\_PATENT_{it}$	# of patents by for-profit, non-biotechnology organizations on gene *i* in year *t*	Jensen and Murray; USPTO; author verification
$OTHERPUBLIC\_PUBLICATION_{it}$	# of publications by nonprofit, nonuniversity research organizations on gene *i* in year *t*	Entrez Gene; PubMed; author verification
$OTHERPUBLIC\_PATENT_{it}$	# of patents by nonprofit, nonuniversity research organizations on gene *i* in year *t*	Jensen and Murray; USPTO; author verification
$UNIV\_PUBLICATION_{it}$	# of publications by universities on gene *i* in year *t*	Entrez Gene; PubMed; author verification
$UNIV\_PATENT_{it}$	# of patents by universities on gene *i* in year *t*	Jensen and Murray; USPTO; author verification
Independent Variables and Control Variables		
GENE (i = 61)	Dummy variables for 61 gene ids	Entrez Gene
BIO	1 if publications and patents are generated by BIO and 0 if by UNIV	Author verification
PHARMA	1 if publications and patents are generated by PHARMA and 0 if by UNIV	Author verification

OTHERPUBLIC	1 if publications and patents are generated by OTHERPUBLIC and 0 if by UNIV	Author verification
APPLIED STAGE$_{it}$	1 if YEAR$_t$ comes after the first publication of allelic variant on gene id *i*	OMIM; author verification
APPLIED STAGE$_{it}$ * BIO	Interaction term between APPLIED STAGE$_{it}$ and BIO	Author verification
APPLIED STAGE$_{it}$ * PHARMA	Interaction term between APPLIED STAGE$_{it}$ and PHARMA	Author verification
APPLIED STAGE$_{it}$ * OTHERPUBLIC	Interaction term between APPLIED STAGE$_{it}$ and OTHERPUBLIC	Author verification
FIRST_PUB_YEAR$_i$	Year of the first publication associated with gene id *i*	Entrez Gene; PubMed
FIRST_PAT_YEAR$_i$	Application year of the first patent associated with gene id *I*	Jensen and Murray; USPTO; author verification
FIRST_YEAR$_i$	min {FIRST_PUB_YEAR $_i$, FIRST_PAT_YEAR$_i$ } in gene id *i*	Author verification
YEAR$_t$	Year *t*	PubMed; author verification
AGE$_{it}$	YEAR$_t$ - FIRST_YEAR$_i$	Author verification
ADJUST2$_t$	YEAR$_t$ - 1980 if YEAR$_t$ ≥ 1981; otherwise 0	Author verification
ADJUST3$_t$	YEAR$_t$ - 1988 if YEAR$_t$ ≥ 1989; otherwise 0	Author verification
ADJUST4$_t$	YEAR$_t$ - 1995 if YEAR$_t$ ≥ 1996; otherwise 0	Author verification
ADJUST5$_t$	YEAR$_t$ - 2000 if YEAR$_t$ ≥ 2001; otherwise 0	Author verification

The dependent variables are the number of publications and patents. Thus, four pairs of publications and patents serve as key dependent variables: (BIO_PUBLICATION, BIO_PATENT), (PHARMA_PUBLICATION, PHARMA_PATENT), (UNIV_PUBLICATION, UNIV_PATENT) and (OTHERPUBLIC_PUBLICATION, OTHERPUBLIC_PATENT.) The average number of publications across research organizations ranges from 0.04 to 1.52 per year, with those from universities numbering the highest and those from pharmaceutical companies numbering the lowest. The average number of patents per year ranges from 0.04 to 0.17, with the number from biotech startups being the highest and the number from other public research organizations being the lowest. For U.S. organizations, the average number of publications per year ranges from 0.01 to 0.65 and the number of patents per year from 0.03 to 0.17. The organizations producing the highest and lowest numbers of publications and patents are similar except for the number of patents per year by pharmaceuticals, which is lowest among U.S. organizations.

The control variable for research project is GENE, which comprises 61 gene ids. The GENE variable controls for the heterogeneity of knowledge underlying research paths. Other key control variables are AGE, PERIOD and ADJUSTs, the term modifying the effect of AGE in a specific PERIOD. AGE ranges from 0 to 32, with a mean of 10 years; the 75th percentile of AGE is 15. PERIOD dummies range from 0.05 to 0.31, with 77 percent of observations falling into PERIOD_3 through PERIOD_5**.** This implies that many research projects either continued or recently started.

Table 3.3. Summary Statistics

Variable	Observation	Mean	Standard Deviation	Min	Max
Dependent Variables					
$BIO\_PUBLICATION_{it}$	1167	0.054	0.245	0	2
BIO_PATENT_{it}	1167	0.178	0.631	0	6
$PHARMA\_PUBLICATION_{it}$	1167	0.046	0.237	0	2
$PHARMA\_PATENT_{it}$	1167	0.060	0.269	0	3
$OTHERPUBLIC\_PUBLICATION_{it}$	1167	0.485	0.940	0	7
$OTHERPUBLIC\_PATENT_{it}$	1167	0.046	0.251	0	3
$UNIV\_PUBLICATION_{it}$	1167	1.528	2.567	0	22
$UNIV\_PATENT_{it}$	1167	0.073	0.333	0	4
Independent Variables and Control Variables					
BIO	2334	0.5	0.5	0	1
PHARMA	2334	0.5	0.5	0	1
OTHERPUBLIC	2334	0.5	0.5	0	1
APPLIED $STAGE_{it}$	1167	0.577	0.494	0	1
APPLIED $STAGE_{it}$ * BIO	2334	0.288	0.453	0	1
APPLIED $STAGE_{it}$ * PHARMA	2334	0.288	0.453	0	1

APPLIED STAGE$_{it}$ * OTHERPUBLIC	2334	0.288	0.453	0	1
AGE$_{it}$	1167	10.051	7.050	0	32
ADJUST2$_{t}$	1167	14.068	6.768	0	24
ADJUST3$_{t}$	1167	6.922	5.435	0	16
ADJUST4$_{t}$	1167	2.351	3.061	0	9
ADJUST5$_{t}$	1167	0.522	1.138	0	4
Others					
FIRST_PUB_YEAR$_{i}$	1167	1983	6.262	1972	1997
FIRST_PAT_YEAR$_{i}$	1167	1993	5.213	1978	2000
FIRST_YEAR$_{i}$	1167	1983	6.161	1972	1997
YEAR$_{t}$	1167	1993	7.050	1972	2004
PERIOD_1$_{t}$	1167	0.046	0.210	0	1
PERIOD_2$_{t}$	1167	0.178	0.382	0	1
PERIOD_3$_{t}$	1167	0.305	0.460	0	1
PERIOD_4$_{t}$	1167	0.260	0.439	0	1
PERIOD_5$_{t}$	1167	0.209	0.406	0	1

As Figures 3.3 and 3.4 show, the largest portion of research has been initiated recently and therefore lies in recent periods.

Figure 3.3. Publications and Patents by Age

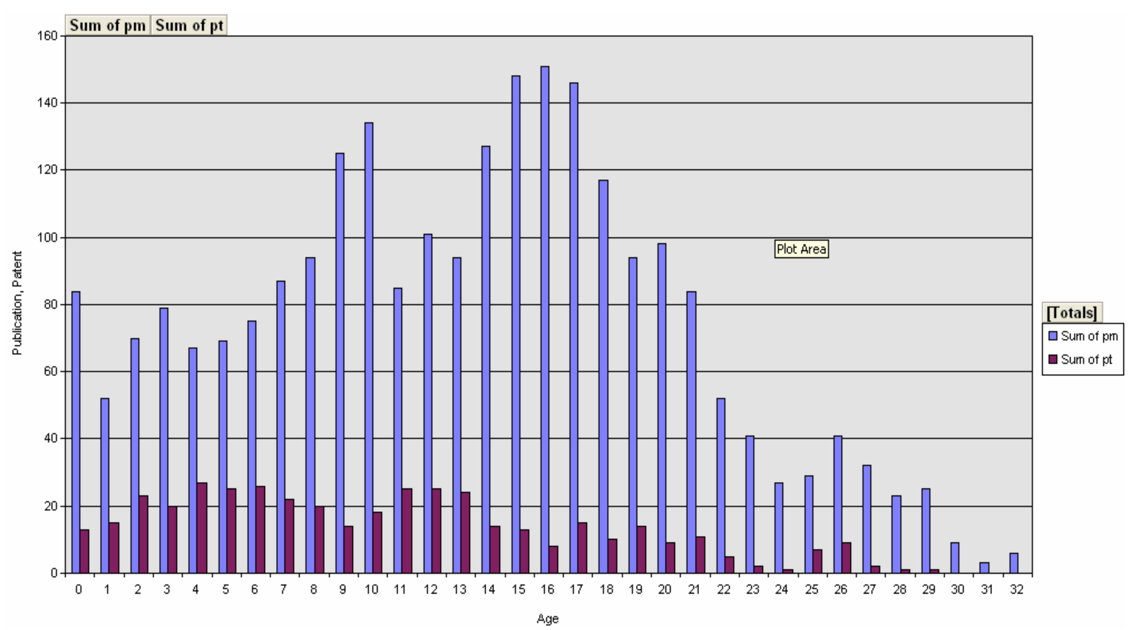
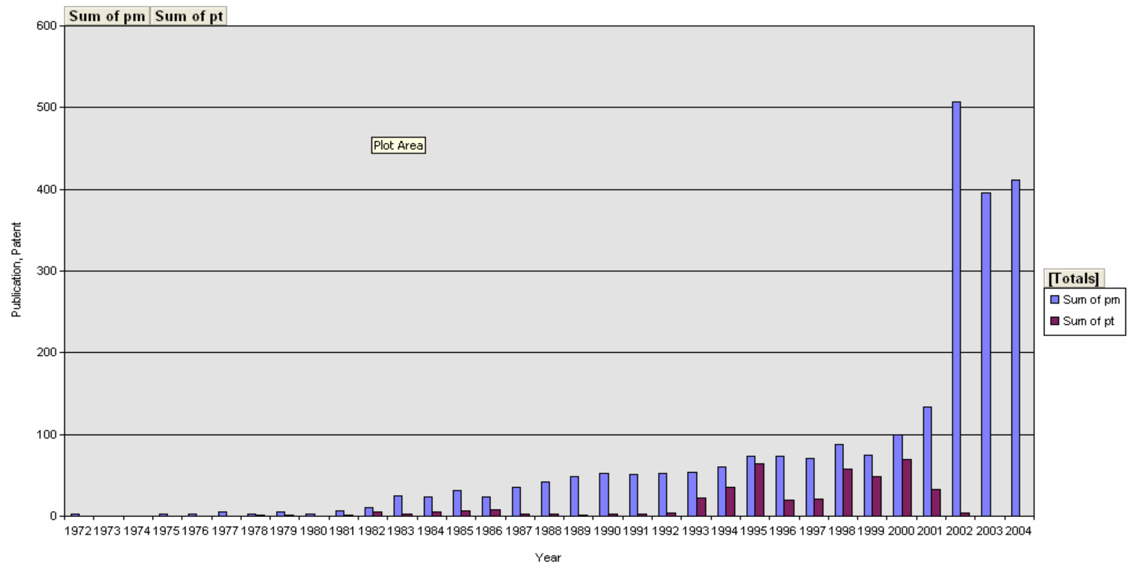


Figure 3.4. Publications and Patents by Year



The main explanatory variables are MANAGER, APPLIED STAGE and their interaction terms. The MANAGER variable equals one when the organizational affiliation is the managed-research type: bio, pharmaceuticals or other public research organizations. Its value is 0 when the organizational affiliation is the unmanaged-research type, i.e., universities. Therefore, being a MANAGER variable equal to one means the change in decision rights on the disclosure from a researcher to a manager. Each type has 1,167 observations for publications and patents. APPLIED STAGE is a dummy variable that equals 1 if the current year is after the publication year of allelic variant in OMIM. APPLIED STAGE affects 57.7 percent of observations. The main focus of this paper is the interaction terms, which represent the response of researchers under different types of organization in the applied stage.

3.6.3. Changes in publications and patents after the discovery

Table 3.4 shows the preliminary analysis of the changes in publication and patenting behavior across types of research organization following the discovery of a disease-causing gene mutant. In for-profit organizations, the number of publications does not seem to change following the discovery, and the number of patents barely changes. The directions in BIO and PHARMA appear to be the opposite (-0.01 for BIO vs. 0.01 for PHARMA). For nonprofit organizations, the direction seems to be clearer: The number of publications increases following the discovery, with publications from universities increasing the most (1.13). However, other public research organizations seem to increase patent applications, but universities do not seem to be affected by the discovery. Thus, research organizations seem to respond differently to the same discovery in terms of publication and patenting behaviors. For instance, for-profit organizations do not seem to respond much to the discovery, and nonprofit organizations respond by more publication in the applied research stage.

Table 3.4. Conditional Mean in Publications and Patents after the Discovery

	Profit				Nonprofit			
	BIO		PHARMA		OTHERPUBLIC		UNIV	
	Pub	Pat	Pub	Pat	Pub	Pat	Pub	Pat
Total	0.05	0.17	0.04	0.06	0.48	0.04	1.52	0.07
Before	0.05	0.18	0.04	0.05	0.28	0.02	0.87	0.07
After	0.05	0.17	0.04	0.06	0.63	0.06	2.00	0.07
Diff	*0.00*	*-0.01*	*0.00*	*0.01*	*0.35*	*0.04*	*1.13*	*0.00*

Finally, comparing publication numbers from biotech (pharmaceuticals) researchers and university researchers shows a significant reduction in publication rate, 0 vs. 1.13 (0 vs. 1.13), after the discovery. The numbers in patent change little (-0.01 vs. 0 and 0.01 vs. 0, respectively) after the discovery. These seem to imply that the change in the control rights over disclosure hinders the disclosure of scientific findings in the form of publication. When researchers in other public research organizations and universities are compared, the change in the control rights over disclosure seems to lead to the reduction of publication (0.35 vs. 1.13) and the increase in patent (0.04 vs. 0.00) in the applied stage. In the next section, these preliminary observations are analyzed further by adopting an econometric method.

3.7. Empirical Results

This section estimates the effect of organizational form in research on researchers' disclosure of scientific findings in terms of publication and patent in human gene research. From the previous section, researchers in the managed-research-type organization are expected to respond to the advance of applied stage with fewer publications and more patents than researchers in universities. In addition, this effect will be the strongest in the middle of the applied stage because the manager and researcher are not in conflict over how to disclose at the early basic stage or late-stage applications. The empirical analysis proceeds as follows. First, with control variables for project and "piecewise linear" effect of age, section 7.1 implements differences-in-differences analyses to identify the effect of the management on knowledge disclosure. In section 7.2 this paper examines an alternative specification on the effect of age. In section 7.3

the dynamic effect of the management on knowledge disclosure is estimated. To address count data characteristics, all specifications employ a negative binomial regression, and the coefficients are reported as incident rate ratios (IRR). Thus, the coefficient equal to 1 means no effect, greater than 1 a positive effect and less than 1 a negative effect.

3.7.1. Differences-in-differences results

After controlling for research path and temporal variables, the following notable patterns emerge. First, researchers in biotech firms and pharmaceuticals tend to significantly reduce the number of their publications compared to university researchers in the applied stage. Although they tend to increase their patent applications, this effect is not significant compared to university researchers. Second, other public research organizations also significantly increase their protection of scientific findings, especially by patent applications, compared to universities.

Table 3.5 summarizes the BIO-UNIV pair data set results, which regards the BIO as a managed-research type. As Table 3.5-1 indicates, without controls variables and organizational types, publication rate significantly increases following the discovery, whereas patent application rate appears not to be affected in the applied stage of human gene research. After considering relevant controls and organizational type, researchers at biotech firms tend to publish significantly less after the discovery than do university researchers: The researchers in biotech firms are not active publishers in gene research and significantly reduce the publication rate by 51 percent (Table 3.5-3). In contrast, researchers at biotech firms are enthusiastic about patent applications in gene research and tend to increase patent application by 11 percent after they are in the applied stage, compared to university researchers.

Table 3.5. Differences-in-differences of Biotech vs. University

	(3.5-1)		(3.5-2)		(3.5-3)	
	PUBLICA-TION	PATENT	PUBLICA-TION	PATENT	PUBLICA-TION	PATENT
Independent Variables						
APPLIED STAGE	***2.232*** ***(0.243)***	0.988 (0.169)	***1.686*** ***(0.233)***	0.755 (0.192)	***1.606*** ***(0.194)***	0.676 (0.237)
BIO					***0.059*** ***(0.013)***	***2.413*** ***(0.554)***
APPLIED STAGE *BIO					***0.497*** ***(0.141)***	1.117 (0.343)
Control Variables						
GENE (# restrictions = 61)			χ^2 198.16 p-value 0.00	χ^2 14629.24 p-value 0.00	χ^2 331.54 p-value 0.00	χ^2 12675.33 p-value 0.00
AGE			0.931 (0.078)	***2.328*** ***(0.798)***	0.962 (0.750)	***2.239*** ***(0.807)***
ADJUST (PERIOD2)			1.100 (0.113)	***0.337*** ***(0.124)***	1.059 (0.102)	***0.352*** ***(0.135)***
ADJUST (PERIOD3)			0.929 (0.046)	***1.767*** ***(0.191)***	0.941 (0.042)	***1.780*** ***(0.193)***
ADJUST (PERIOD4)			***1.211*** ***(0.059)***	0.875 (0.079)	***1.215*** ***(0.052)***	0.848 (0.078)
ADJUST (PERIOD5)			***1.289*** ***(0.075)***	***0.206*** ***(0.032)***	***1.230*** ***(0.054)***	***0.212*** ***(0.033)***
Regression Statistics						
Log-likelihood	-2580.327	-856.696	-2346.049	-713.087	-1825.769	-696.550
P-value of Chi	0.000	0.000	0.000	0.000	0.000	0.000
# of observations	2334	2334	2334	2334	2334	2334

1. Coefficients are in IRR.
2. Robust standard errors are in parentheses.
3. GENE is Gene Fixed Effect.

Table 3.6 summarizes a similar experiment with the PHARMA-UNIV pair data set. Here, the PHARMA variable, which consists mainly of pharmaceutical companies, is regarded as the managed-research type. Similar patterns are observed. As Table 3.6-1 shows, without considering other control variables, the publication rate and patent rate increase following the discovery (22 percent vs. 18 percent, respectively). After considering control variables and the organizational types, however, the researchers in the pharmaceuticals significantly reduced publications by 48 percent and increased patent applications by 29 percent once the research direction shifted toward applications (Table 3.6-3), compared to university researchers.

Table 3.6. Differences-in-differences of Pharmaceutical vs. University

	(3.6-1)		(3.6-2)		(3.6-3)	
	PUBLICA-TION	PATENT	PUBLICA-TION	PATENT	PUBLICA-TION	PATENT
Independent Variables						
APPLIED STAGE	***2.229 (0.244)***	1.182 (0.225)	***1.574 (0.216)***	***0.456 (0.138)***	***1.500 (0.180)***	***0.406 (0.139)***
PHARMA					***0.054 (0.013)***	0.722 (0.187)
APPLIED STAGE *PHARMA					***0.423 (0.134)***	1.295 (0.439)
Control Variables						
GENE (# restrictions = 61)			χ^2 181.34 p-value 0.00	χ^2 34397.00 p-value 0.00	χ^2 315.36 p-value 0.00	χ^2 30473.38 p-value 0.00
AGE			0.895 (0.073)	1.070 (0.306)	0.913 (0.066)	1.070 (0.303)
ADJUST (PERIOD2)			1.174 (0.121)	0.966 (0.311)	1.153 (0.106)	0.967 (0.310)
ADJUST (PERIOD3)			***0.901 (0.046)***	***1.398 (0.201)***	***0.904 (0.042)***	***1.396 (0.199)***
ADJUST (PERIOD4)			***1.229 (0.061)***	***0.692 (0.070)***	***1.244 (0.054)***	***0.693 (0.069)***
ADJUST (PERIOD5)			***1.271 (0.074)***	***0.360 (0.076)***	***1.203 (0.054)***	***0.360 (0.076)***
Regression Statistics						
Log-likelihood	-2562.292	-573.333	-2330.398	-429.751	-1786.885	-429.051
P-value of Chi	0.000	0.378	0.000	0.000	0.000	0.000
# of observations	2334	2334	2334	2334	2334	2334

1. Coefficients are in IRR.
2. Robust standard errors are in parentheses.
3. GENE is Gene Fixed Effect.

The above results are obtained from data sets that exhibit profit motivation. In addition, during the construction of the data, patenting generating genes might be favored; therefore, the effects of the advance of the applied stage with the BIO and PHARMA types could be overstated. Thus, the effect of discovery under the managed-research type could reflect profit motivation or non-random sampling. To examine this issue of profit motivation, this paper implements a similar examination on the effect of the advance of the applied stage among universities and other public research organizations.

Table 3.7 demonstrates responses of other public research organizations in the applied stage using the OTHERPUBLIC-UNIV pair data set. The OTHERPUBLIC type consists of non-university hospitals, independent research organizations and government research organizations. Strikingly, the OTHERPUBLIC-UNIV data shows patterns similar to previous for-profit organization cases: Other public organizations tend to reduce publications and increase patents compared to universities. Moreover, researchers in other public research organizations significantly prefer patent applications to disclose scientific findings.

As Table 3.7-1 demonstrates, without considering controls and organizational types, more publications and more patents applications are generated in the applied stage (2.2 times vs. 1.4 times, respectively). However, after considering the organizational type, researchers in other public research organizations tend to patent more in the applied stage than do university researchers, while maintaining their publication activity. As shown in Table 3.7-3, researchers in other public research organizations are 2.3 times as likely to patent as university researchers in the application stage of gene research. Given that researchers in the biotechnology industry have similar educational backgrounds (e.g., most of them have Ph.D. degrees) and that they have chosen nonprofit research organizations, this result supports the effect of management (i.e., the control rights over disclosure) predicted by the previous theoretical model.

Table 3.7. Differences-in-differences of Other Public Organizations vs. University

	(3.7-1)		(3.7-2)		(3.7-3)	
	PUBLICA-TION	PATENT	PUBLICA-TION	PATENT	PUBLICA-TION	PATENT
Independent Variables						
APPLIED STAGE	***2.285 (0.202)***	1.401 (0.108)	***1.548 (0.172)***	***0.492 (0.153)***	***1.518 (0.165)***	***0.353 (0.123)***
OTHERPUBLIC					***0.335 (0.036)***	***0.350 (0.110)***
APPLIED STAGE *OTHERPUBLIC					0.974 (0.125)	***2.357 (0.921)***
Control Variables						
GENE (# restrictions = 61)			χ^2 266.27 p value 0.00	χ^2 27495.84 p value 0.00	χ^2 338.35 p value 0.00	χ^2 26592.19 p value 0.00
AGE			0.934 (0.066)	1.073 (0.250)	0.940 (0.062)	1.074 (0.248)
ADJUST (PERIOD2)			1.119 (0.099)	0.877 (0.251)	1.112 (0.092)	0.877 (0.249)
ADJUST (PERIOD3)			0.935 (0.039)	***1.766 (0.318)***	0.937 (0.037)	***1.772 (0.316)***
ADJUST (PERIOD4)			***1.156 (0.453)***	***0.532 (0.062)***	***1.164 (0.043)***	***0.528 (0.061)***
ADJUST (PERIOD5)			***1.312 (0.059)***	***0.197 (0.085)***	***1.269 (0.049)***	***0.200 (0.086)***
Regression Statistics						
Log-Likelihood	-3101.833	-518.164	-2698.567	-381.441	-2522.892	-376.36
P-value of Chi	0.000	0.107	0.000	0.000	0.000	0.000
# of observations	2334	2334	2334	2334	2334	2334

1. Other public organization consists of non-university hospitals, government research organizations and independent research organizations. 2. Coefficients are in IRR. 3. Robust standard errors are in parentheses. 4. GENE is Gene Fixed Effect.

Thus, data seem to support this paper's argument that researchers in non-academic research organizations respond to the advance of the applied stage with fewer publications and more patents than academic researchers due to the control rights over disclosure. For-profit organizations tend to restrict their publication. Other public research organizations tend to protect their findings by patenting.

3.7.2. Effect of AGE on publications and patents

Tables 3.5, 3.6, and 3.7 assume that AGE affects publication and patent application in a specific way, i.e., that the effect of AGE is constant within a period but varying across periods. In publication regressions, as (3.5-3), (3.6-3) and (3.7-3) show, the effect of AGE seems to accelerate from period 4. Although AGE does not seem to affect the publication rate until period 3, the effect surges in periods 4 and 5. In the BIO-UNIV pair (Table 3.5-3), the AGE affects the publication rate only after period 3. During periods 4 and 5, one more year in a specific gene research increases the mean publication rate by 21 percent and 23 percent, respectively, relative to previous periods. The PHARMA-UNIV and OTHERPUBLIC-UNIV pairs demonstrate similar patterns: The effect of AGE becomes significant in periods 4 and 5 (e.g., 16 percent ~ 27 percent increases in publication with AGE in those periods).

In patent regressions, the effect of AGE differs between the BIO-UNIV pair and other pairs. As Table 3.5-3 shows, an additional year in gene research enhances the patent application rate by 2.2 times in the BIO-UNIV pair. The effect of AGE decreases in period 2 by 65 percent, rebounds in period 3 by 78 percent and decreases again in period 4. In case of the PHARMA-UNIV pair (Table 3.6-3), the baseline effect of AGE is around 7 percent. The effect decreases in periods 2 and 4 by 4 percent and 31 percent, respectively, and increases by 40 percent in period 3. Similarly, the OTHERPUBLIC-UNIV pair (Table 3.7-3) shows around 7 percent of baseline AGE effect, 13 percent and 47 percent decreases in periods 2 and 4 respectively, and a 77 percent increase in period 3.

The previous specification is one way to reflect the “period-varying” effect of AGE. A possible alternative is to estimate the effect of AGE by separately considering ages that belong to a given period. This approach assumes that the effect of AGE is not linear. As Table 3.8 demonstrates, main findings from the previous section remain valid even after the different specification on the effect of AGE; for-profit research organizations tend to restrict their publication; other public research organizations prefer using patent; and universities publish more and patent less in the applied stage of human gene research.

Table 3.8. Differences-in-differences using an Alternative Age Effect

	(3.8-1) BIO-UNIV		(3.8-2) PHARMA-UNIV		(3.8-3) OTHERPUBLIC-UNIV	
	PUBLICA-TION	PATENT	PUBLICA-TION	PATENT	PUBLICA-TION	PATENT
Independent Variables						
APPLIED STAGE	***1.908*** ***(0.229)***	0.641 (0.207)	***1.757*** ***(0.209)***	***0.362*** ***(0.121)***	***1.740*** ***(0.187)***	***0.267*** ***(0.087)***
MANAGER	***0.060*** ***(0.013)***	***2.457*** ***(0.548)***	***0.055*** ***(0.013)***	0.713 (0.178)	***0.335*** ***(0.036)***	***0.373*** ***(0.107)***
APPLIED STAGE*MANAGER	***0.495*** ***(0.138)***	1.093 (0.325)	***0.424*** ***(0.133)***	1.318 (0.441)	0.969 (0.122)	***2.192*** ***(0.813)***
Control Variables						
GENE (# restrictions = 61)	χ^2 374.74 p-value 0.00	χ^2 16132.29 p-value 0.00	χ^2 370.26 p-value 0.00	χ^2 52.94 p-value 0.00	χ^2 441.58 p value 0.00	χ^2 63.81 p value 0.00
AGE (PERIOD1)	***0.773*** ***(0.088)***	0.556 (0.241)	0.830 (0.091)	***0.000*** ***(0.000)***	***0.806*** ***(0.083)***	***0.000*** ***(0.000)***
AGE (PERIOD2)	1.022 (0.030)	1.095 (0.067)	1.045 (0.031)	1.118 (0.116)	***1.051*** ***(0.027)***	1.283 (0.181)
AGE (PERIOD3)	0.988 (0.016)	***1.108*** ***(0.039)***	1.002 (0.016)	***1.243*** ***(0.063)***	1.016 (0.014)	***1.411*** ***(0.102)***
AGE (PERIOD4)	0.988 (0.010)	***1.136*** ***(0.026)***	1.009 (0.010)	***1.185*** ***(0.041)***	1.011 (0.009)	***1.260*** ***(0.059)***
AGE (PERIOD5)	***1.085*** ***(0.008)***	1.014 (0.023)	***1.095*** ***(0.008)***	1.021 (0.032)	***1.097*** ***(0.007)***	***0.857*** ***(0.061)***
Regression Statistics						
Log-likelihood	-1820.289	-742.945	-1784.318	-443.601	-2510.989	-380.063
P-value of Chi	0.000	0.000	0.000	.	0.000	.
# of observations	2334	2334	2334	2334	2334	2334

1. MANAGER is 1 if biotech, pharma, and other public in each pair
2. Coefficients are in IRR.
3. Robust standard errors are in parentheses.
4. GENE is Gene Fixed Effect.

3.7.3 Dynamic effects

As predicted in the previous section, the impact of management will be the strongest in the middle of the applied stage because researchers and managers are not in conflict over the optimal disclosure strategy at the early basic stage or the late applied stage. After analyzing interaction terms between organizational type and applied stage with multiple time windows, the following patterns emerge: First, researchers at biotech firms progressively reduce the number of publications more than do university researchers as research advances to the more applied stages. Moreover, this effect is the strongest in the middle of the applied stage and becomes insignificant in the latter part of the applied stage. Second, researchers in other public research organizations progressively increase their patent applications as research moves to the more applied stage; this increase is the most significant in the early and middle years in the applied stage.

Figure 3.5 shows how the coefficient of interaction term APPLIED STAGE*MANAGER changes over the years in the applied stage in reference to biotech firms and universities' publications. The five-year time window is used in this figure. As figure 3.5 illustrates, biotech researchers significantly reduce their publications up to 80 percent relative to university researchers. Moreover, this effect of the management of research was the strongest around the 20th year of the applied stage. Although it is not reported here, similar patterns are observed when three- and four-year windows are adopted.

Figure 3.5. Dynamic Effects on Publication in the Applied Stage

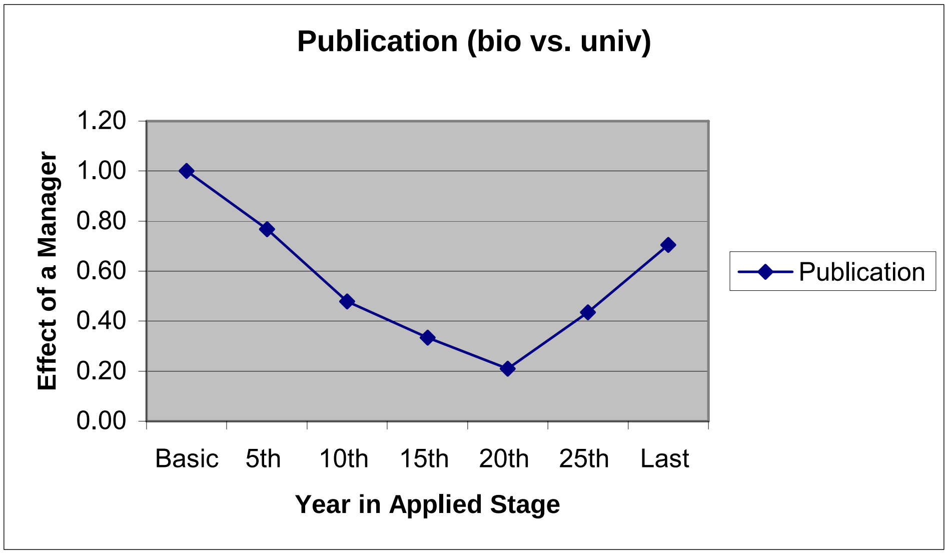
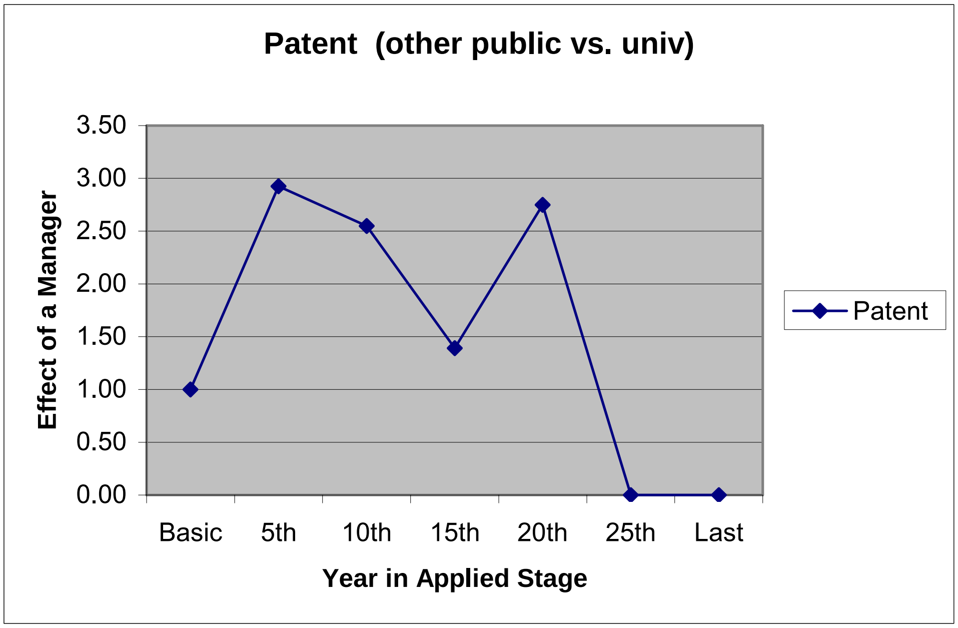


Figure 3.6 demonstrates the dynamics of interaction term APPLIED STAGE*MANAGER in regard to patent applications by other public research organizations and universities. As shown in figure 3.6, the prediction on the effect of organization seems to be supported: Researchers in other public research organizations significantly increase their patent application up to three times more than university researchers around the fifth to 10th years of the applied stage. This organization effect becomes insignificant after the 15th year of the applied stage. Although it is not reported here, similar patterns are observed when three- and four-year windows are adopted. Thus, these pieces of evidence support that the control rights over research discretion affects the disclosure of scientific findings.

Figure 3.6. Dynamic Effects on Patent in the Applied Stage



3.8. Conclusion

This paper provides empirical evidence on how the control rights over research discretion within an organization affects the disclosure of scientific findings by showing that researchers in academic and non-academic research organizations respond differently to the advance of the applied stage in human gene research. The evidence suggests the following: (a) Researchers in non-academic research organizations publish less and patent more than university researchers following a discovery that can spark intensive research for commercialization; (b) researchers in biotech firms and pharmaceuticals reduce their publications to protect their findings; (c) researchers in other public research organizations increase their patents applications more than do university researchers; and (d) these effects are the strongest in the middle of the applied stage.

This paper's approach and main argument that the distribution of research discretion within a research organization can affect a researcher's disclosure of scientific knowledge can be extended further to analyze the relationship between knowledge and organizations. Prospective applications are as follows:

A systematic approach to public research organizations. The control-rights approach to research organizations seems to shed light on subtle difference between university and other public research organizations such as government research agencies. Dasgupta and David (1994) also detect the distinction when they differentiate "mission oriented research" from "open science." This control-rights approach may allow us to examine the implication of this organizational difference between public organizations on the disclosure of scientific knowledge. Thus, there may be division of roles in the production and dissemination of scientific knowledge even among public research organizations – the university as a producer and government agencies as more focused coordinators. This raises the concern that the subtle balance between open science and technology can become an issue even in research collaboration among public research organizations. The tension between universities and the Department of Defense over publication of joint research results is a case in point.

*Analysis of the conditions for successful R&D collaboration*s. The finding that research organizations respond differently to a scientific discovery may suggest another condition for successful R&D collaborations between organizations exerting different control rights contracts. For example, the collaboration between universities and private firms tends to be put under tension due to the different incentives to disclose their joint research results, if the joint scientific discovery contains various application prospects. Thus, the rights to protect their joint research results should be carefully allocated to achieve a successful collaboration.

Policy Implications in R&D. The results of this paper imply that policy makers should be cautious when they want to encourage for-profit firms to participate in research projects. Suppose a research project has a high potential for various applications. If for-profit firms are encouraged to participate in the project too early, then access to research studies may be over-restricted as the project develops, unless other policy measures are considered. Although the participation of private firms may serve public interests by providing necessary funds and research staff, policy makers also should mitigate their incentives to restrict the research results after they discover potential for applications.

Managerial Implication. Because whether scientists have research discretion in scientific research can affect researchers' incentive to disclose their findings, managers can enhance organizations' performances by strategically delegating to researchers. If the project is in basic stage, then a manager may be better off by not intervening in researchers' activities. If the project is in the applied stage, however, directing researchers to conduct research a manger believes is necessary can lead to better performance in terms of organization.

CHAPTER 4

Where does a firm seek its productive knowledge?

The locus of industrial research

4.1. Introduction

Industrial R&D is often considered to be the engine for innovation and growth in an economy. In 2004, industrial R&D in the U.S. constituted sixty four percent of national R&D expenditure (National Science Foundation 2006). To improve R&D efficiency and firms' performance, U.S. corporations recently have been reorganizing their research activities by strengthening collaboration with universities and research-oriented firms while reducing in-house efforts. For example, from 1993 to 2003, the annual growth rate of contracted R&D in companies increased to almost double that of in-house R&D (National Science Foundation 2006). This reflects a shared belief between industry executives and policy makers that corporate research divisions need to focus more on monitoring and evaluating external technologies. During the 1980s, alerted by a remarkable advance of foreign corporations into the U.S. market, researchers began analyzing how Japanese firms especially had been so successful in generating marketable innovations at a rapid pace. Their analyses suggested that Japanese firms organized their corporate research around "scanning" the external technological environment and involving manufacturing divisions in the R&D process, whereas U.S. corporations were doing the opposite (Mowery and Rosenberg 1989). Inspired partly by the performance of Japanese research management and partly by intensified competition, central research labs of U.S. corporations have been reorganized to more rapidly incorporate external technological advances (Buderi 2000). Although the practice of vertically disintegrating research activities to commercialize scientific knowledge has become popular, in-house research divisions were not always ineffective in producing commercializable innovations.

Researchers reported that corporate research labs detached from production could generate breakthrough innovations, which led to subsequent innovations using “big science” (Hounshell 1996; Mowery and Rosenberg 1989). For example, DuPont’s research team produced nylon based on the polymer theory, and AT&T’s research team produced the transistor based on solid state physics (Hounshell 1996; Mowery and Rosenberg 1989). Thus, there were instances in which the vertically integrated research divisions successfully functioned by reducing transaction costs and effectively adapting technology to a firm’s production (Dosi 1988). As a result, the proportion of contracted-out R&D in manufacturing was still less than five percent in 2003 (National Science Board 2006). Moreover, the recent literature on product development reports that a vertically integrated structure enhances firms’ performance over the entire product cycle (Macher 2006; Novak and Stern 2006). So when does a firm want to vertically integrate research activities to use its in-house research division as a generator of the “big science” innovation strategy? In contrast, when does a firm want to “disintegrate” their research activities and source a new innovation? How will this organizational decision affect the pattern of innovation and firms’ performance?

This paper examines factors that affect the make-or-buy decision on corporate research activities and the relation between the vertical integration of a firm's research and different types of innovation. To do so, this paper stresses that corporate research is embedded in the production process and that the make-or-buy decision on research needs to consider its effect on the production speed. Specifically, making a technology in-house can result in a longer research period for the firm because the firm has limited amount of knowledge. It will lower adaptation costs, however, because production requires product-specific knowledge. In contrast, buying a technology from the marketplace can save research time, but incur a larger adaptation cost in production stage because inter-organizational knowledge transfer is costly. To resolve this make-or-buy decision on technology, a firm will consider the trade-off between time savings in research stage and adaptation cost in production stage because a firm's ultimate goal is to produce goods by using a technology developed in research stage. As a result, under reasonable conditions, a firm is likely to produce a technology with broader applications in-house; in contrast, a firm is likely to purchase a technology with narrower applications from the marketplace.

This study can contribute to the literature on research boundaries of a firm (a) by introducing adaptation cost in production stage as a key factor in deciding the boundary, (b) by providing a microeconomic foundation on how organizational design can affect the performance of research activities and types of innovations and (c) by predicting the effect of the reorganization of corporate research labs on the types and rate of innovations in our economy. This paper is organized as follows: Section 4.2 reviews the existing literature; Sections 4.3 and 4.4 provide a formal model and main propositions; and Section 4.5 discusses future research directions.

4.2. Literature Review

Speculations on why firms perform basic research inside their boundaries have been controversial because their investments in basic research do not seem to generate immediate revenue. In their seminal papers, Cohen and Levinthal (1989, 1990) show that in addition to productivity increase, R&D investments enhance firms' capability of evaluating and learning about external technological opportunities ("absorptive capacity"). Although the absorptive capacity literature expands our understanding of the role of investments in basic research, it does not explicitly address how firms strategically choose between producing new knowledge in-house and acquiring new knowledge from the marketplace. Thus, it does not seem to satisfactorily explain why the locus of basic research of business corporations has varied in the last century.

Researchers report that firms have strategically organized their R&D activities in and out of their boundaries. According to business and economic historians, U.S. firms in the early twentieth century did not seem to systemically organize the basic research function inside the firm (Hounshell 1996). As market competition became intense and technology advantage dwindled, firms such as General Electronics, AT&T and DuPont began to found centralized in-house research programs to address "competitive threats to their business and core technologies"(Hounshell 1996). The centralized in-house research labs performing basic research became nationally popular during the times of war (Hounshell 1996; Mowery 1983; Mowery and Rosenberg 1989). Impressed by the remarkable achievement of "R&D pioneers" and scientists during the wars, firms were swayed by "big science" inventions and regarded in-house research labs performing basic research as strategic tools to obtain new markets and supra-normal profit. More than half of all industrial R&D laboratories founded until 1946 were established between 1919 and 1936, and industrial research grew even in the Great Depression (Hounshell 1996). However, the return to R&D investment declined during the mid-1970s, and the paradigm that firms can generate big inventions by letting in-house research laboratories focus on basic research was challenged by both management and policy makers (Mowery and Rosenberg 1989). Especially, advance of Japanese firms in the U.S. market triggered research interests in the management of innovation within the Japanese firms. They had "focused on an incremental strategy" of internal R&D and supplemented this strategy with extensive screening of the environment to generate innovation (Mowery and Rosenberg 1989). Inspired by this observation, U.S. corporations re-evaluated their R&D organizations and strategy, and deployed basic research outside firms again. In 1990s, these assessments materialized as a "bloodbath" to giant corporate research labs such as AT&T's Bell lab and IBM's Thomas J. Watson Research Center (Buderi 2000). These historical observations compel us to ask the following question: If firms can enhance their absorptive capacities by performing basic research, why have major U.S. corporations shifted their locus of basic research in and out of their boundaries, instead of keeping increasing investment in in-house basic research?

This issue of the R&D boundaries of a firm has been examined by scholars in management and economics. Pisano (1990) examined whether pharmaceutical companies develop new biotechnology-based products through in-house R&D vs. contractual arrangements with outside firms. The research boundaries depend on (a) small-number-bargaining hazards due to specialized R&D capabilities and (b) appropriability concerns due to product market competition (Pisano 1990). Pisano tested the effect of these transaction costs on the R&D boundaries of a firm and demonstrated that small-number-bargaining hazards provided firms with the incentive to internalize their R&D, but product market competition did not. Bajari and Tadelis (2001) formalized the trade-off between incentives and ex post renegotiation cost based on transaction cost economics and examined the choice between a “fixed cost” contract and a “cost plus” contract. The authors showed that the complexity of a project favors a cost plus contract over a fixed cost contract because the cost plus contract will achieve low ex post renegotiation cost and will not dissipate ex post surplus. By reinterpreting the cost plus contract as internal production, they applied their framework to the make-or-buy decision and suggested that a complex component would be produced internally.

Different from this transaction cost approach, Aghion and Tirole (1994) theoretically examined the same issue in relation to incomplete contracts and property rights theory: Innovation itself is non-contractible because it is almost impossible to describe its quality and delivery timing. Thus, contracting parties such as a research unit and a “customer” of research can contract only upon the allocation of property rights on future innovation ex-ante, which determines the boundaries of R&D. They concluded that research is more likely to be performed inside a firm if (a) the marginal efficiency of a firm’s contribution is higher than that of a research unit and (b) the ex-ante bargaining power of a firm is stronger than that of a research unit.

In addition to transaction cost and property rights issues, Mowery (1995) insisted that research needed to be inside a firm because (a) innovative knowledge comes not only from scientific research labs, but from other activities such as production and (b) innovative knowledge is hard to transfer within an organization and between organizations. As an explanation of why the boundaries of industrial research have varied, he cited the development of other institutions such as universities, the role of federal R&D and changes in antitrust policy. Although these theoretical and empirical explanations gave insights into the R&D boundaries of a firm, these researchers did not explicitly address how the vertical integration decision would affect innovative outcomes and firms' performance. In addition, as Mokyr (1995) pointed out, the literature tended to "treat technology as undifferentiated outcome" and did not pay attention to research activity in terms of the production development process.

Recent empirical literature on product development addresses the effect of vertical integration on a firm's performance. Macher (2006) compared performance differences between firms specialized in manufacturing and those integrated in product design and manufacturing in the semiconductor industry. The author showed that the vertical integration would enhance the speed and quality of problem solving when technical problems were complex. In contrast, when technical problems were simple, specialized firms showed higher performance. Novak and Eppinger (2001) performed a similar experiment with data from the automobile industry. The authors demonstrated that in-house production is more attractive when the product is complex, and outsourcing is more attractive when the product is simple. Moreover, they informally showed that the complementarity between complexity and vertical integration is related to firms' quality performance. For example, the quality of a complex product will be higher if produced in-house rather than if outsourced. Although the literature provides deep insights on the effect of vertical integration by explicitly incorporating corporate R&D into production process, it has mainly focused on the complexity of a final product and does not explicitly address the relation between knowledge from the R&D stage and the final products to which the knowledge is applied.

Technological knowledge is a special input with unique characteristics. Romer (1990) pointed out that knowledge generated by research activity can be used as an input without preventing others from using it (“nonrivalry”) and that the benefit of using the knowledge is only partially appropriable to the original inventor (“partially excludable”). He stressed the characteristics of R&D as a productive intermediate good by using an example of a “new design.” Because of nonrivalry, a new design can be applied to a certain range of products that a firm plans to produce in its plant. To produce final goods, however, this new design should be implemented within a firm, and the production of goods requires “specific practices” (Mowery and Rosenberg 1989; Nelson and Wright 1992; Vonortas 1997; Mokyr 2002). Thus, to understand the effectiveness of a corporate research lab as a producer vs. an acquirer of technological knowledge, we need to examine how the sourcing of new knowledge will influence costs and benefits during the entire production process. If new knowledge from in-house research is easily adapted to a given range of products, the role of in-house research division as a generator of technology will be more productive. In contrast, if new knowledge from the marketplace can be easily adapted to production, a firm’s research division will be more effective as an acquirer of the technology. Therefore, this paper will examine the relationship between the research boundaries of a firm and types of target technologies: Types of technologies will be characterized in terms of the range of applications to which a technology is applied to capture the nonrival nature of research input.

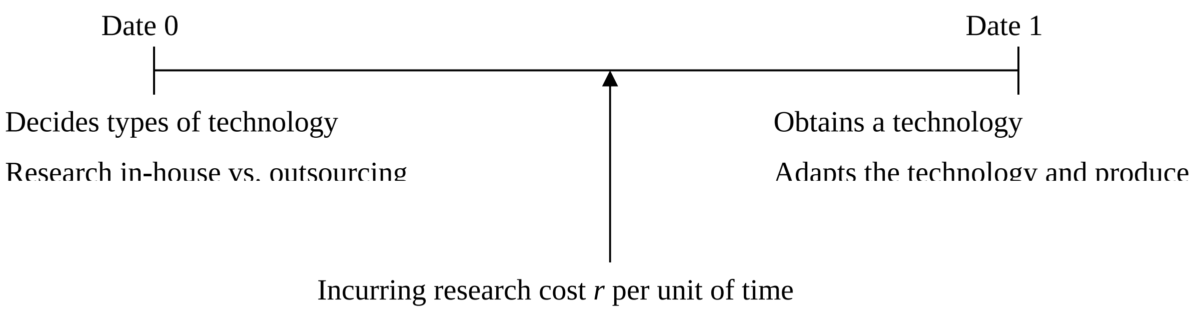
4.3. Model

Production of Technology and Goods. A firm transforms an innovative idea into a marketable product in two steps: First, it generates a "new design (technology)." Second, it adapts the new design to produce distinct goods. From this point on, this paper will use the terms new design and technology interchangeably. A new design is assumed to exogenously "arrive" at a firm following an exponential distribution with a parameter λ. The firm will incur a research cost at the rate *r* per unit of time until it obtains a design. After obtaining it, a firm produces goods by adapting this design to the production of each good. The number of distinct goods to which the design can be applied is *n* and bounded by a finite *N*. Technology will be regarded as having a "broad range" if the technology can be adapted to goods more than a certain critical value n^*. Otherwise a technology will be regarded as having a "narrow range." Whenever a firm adapts the design to a specific good *i*, it incurs an adaptation cost $\alpha(i), i \in \{1,...,n\}$. This paper assumes that $\alpha(i) = \alpha$ for all $i \in \{1,...,n\}$. After incurring this adaptation cost, a firm produces and markets each good. Each good *i* generates market value $V(i)$. This paper assumes that there is no economies of scope and that $V(i) = V$ for all $i \in \{1,...,n\}$. Finally, this paper assumes that a firm has complete information on all variables in this model.

In-house development vs. outsourcing. When a firm generates a technology, it can develop the technology in-house or buy from external research organizations such as universities and independent research centers. From a firm's point of view, the external research organizations can be regarded as one sector and are likely to generate commercializable ideas faster than a single firm because the knowledge sector as a whole specializes in knowledge production and performs a broad range of experimentation. Thus, in-house development will reduce the discovery rate λ so that $\lambda_{in} < \lambda_{out}$. A firm using external knowledge in production, however, can incur a higher adaptation cost because production requires product-specific knowledge and the inter-organizational transfer of productive knowledge is more difficult than the intra-organizational transfer (Mowery 1995). Thus, in-house development will reduce the adaptation cost α per each type of goods so that $\alpha_{in} < \alpha_{out}$. This paper assumes that $\alpha_{in} = \alpha$, $\alpha_{out} = \theta\alpha$ where $\theta > 1$ represents adaptation cost disadvantage. This paper assumes that $V - \theta\alpha > 0$.

Sequence of Events. The timing is as follows: At date zero, a firm chooses the number of possible applications from exogenously give *n* and decides how to generate a technology in-house vs. outsourcing. After these choices, the firm obtains a technology according to the exponential distribution with parameter λ. The parameter depends on what method the firm chooses to generate the technology in the previous stage. From date zero, the firm incurs research cost *r* per unit of time. Because this paper assumes that the ability of researchers in and out of a firm is equal, the decision about where to get technology will not affect the unit research cost *r*. At date one, which will be stochastically determined according to the chosen method, the firm obtains a technology, adapts it to produce goods and markets these goods. In case of technology outsourcing, a firm will pay the incurred research cost as a price for the technology. The sequence of events is illustrated as follows:

Figure 4.1. Sequence of Events



Payoffs. A firm's expected payoff is as follows:

$$\Pi(in-house) = \delta^{1/\lambda_{in}}\left(nV - n\alpha - r/\lambda_{in}\right)$$

$$\Pi(outsourcing) = \delta^{1/\lambda_{out}}\left(nV - n\theta\alpha - r/\lambda_{out}\right)$$

, where $\delta \in (0,1)$ is time preference per unit of time. These pay-offs illustrate that the main trade-off in the research boundary is between time savings in research stage and adaptation cost in production stage. Suppose that a firm chooses the outsourcing method. The increase in the discovery rate λ will increase the expected discount rate $\delta^{1/\lambda_{out}}$ and reduces the expected research cost r/δ_{out}. These effects can be offset, however, by the increase in adaptation cost by θ. This trade-off will affect the firm's decision on whether to produce a broad range technology.

4.4. Results

In this section, we examine how the types of technologies and strategies of developing the technologies can be associated. Technology with broader range of possible applications is likely to be generated in-house if adapting the technology to the production is costly. The following proposition 1 provides conditions on when a firm is likely to develop a fundamental technology in-house.

LEMMA 6. *The optimal number of applications is n*.

PROOF. From linear expected payoffs and the assumption that $V - \theta\alpha > 0$, a firm will optimally choose *n*. □

PROPOSITION 7. *Suppose that* $\alpha/V > \left(\delta^{1/\lambda_{out}} - \delta^{1/\lambda_{in}}\right)/\left(\theta\delta^{1/\lambda_{out}} - \delta^{1/\lambda_{in}}\right)$. *If* $\delta^{1/\lambda_{in}}\left(1/\lambda_{in}\right) > \delta^{1/\lambda_{out}}\left(1/\lambda_{out}\right)$, *then there exists a strictly positive* n^* *such that a firm chooses in-house development if* $n \geq n^*$ *and outsourcing if* $n < n^*$.

PROOF. See Appendix C. □

Intuitively, even if a firm can obtain a technology by outsourcing more quickly than by in-house development, adaptation cost in production stage can offset the advantage of outsourcing in research stage. The advantage of early discovery will be offset if adaptation cost α relative to value V is larger than $\left(\delta^{1/\lambda_{out}} - \delta^{1/\lambda_{in}}\right)/\left(\theta\delta^{1/\lambda_{out}} - \delta^{1/\lambda_{in}}\right)$. Moreover, if the range of applications is broad (i.e., $n \geq n^*$), adaptation costs are likely to favor in-house development over outsourcing because each application incurs the higher adaptation cost under outsourcing.

Remark. If a firm chooses to develop a technology in-house, the expected length $1/\lambda_{in}$ of the development will be longer than if a firm chooses to purchase a technology from the market-place. In the latter case, the expected length of the development will be $1/\lambda_{out}$. Thus, if technology is outsourced, we tend to observe more rapid technological change in narrower products on average.

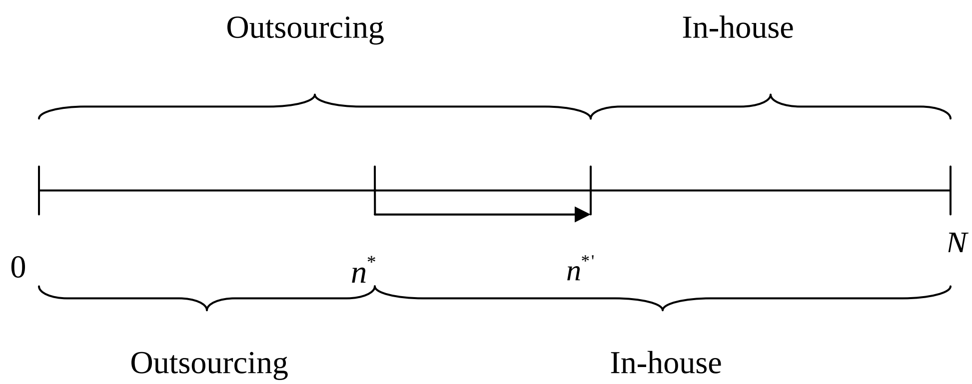
Remark. If adaptation cost α is sufficiently smaller relative to market value V , then a firm is willing to buy a fundamental technology from the marketplace because the advantage of outsourcing in terms of time saved in the research stage becomes more significant than its disadvantage in adaptation cost at the production stage. Suppose $\alpha/V < \left(\delta^{1/\lambda_{out}} - \delta^{1/\lambda_{in}}\right) \Big/ \left(\theta\delta^{1/\lambda_{out}} - \delta^{1/\lambda_{in}}\right)$ and $\delta^{1/\lambda_{in}}\left(1/\lambda_{in}\right) < \delta^{1/\lambda_{out}}\left(1/\lambda_{out}\right)$, that is, adaptation cost is sufficiently low. Then, if $n < n^*$, a firm will develop a technology in-house. If $n \geq n^*$, it will buy it from the marketplace.

The mode of technology production (in-house vs. outsourcing) will be affected by the critical value n^*. If the critical value n^* increases, a technology that a firm could previously generate in-house can be outsourced. The following proposition illustrates how this critical value n^* will be affected by changes in parameter values.

PROPOSITION 8. *(a) If adaptation cost disadvantage θ becomes smaller, n^* will increase. (b) If adaptation cost α becomes smaller, n^* will increase. (c) If the value of each product increases, n^* will increase. (d) If research cost r increases, n^* will increase. If n^* increases, a firm is likely to purchase a new technology from the marketplace*

PROOF. See Appendix C. □

Figure 4.2. Change in the critical value n^* and the research boundary of a firm



Intuitively, as adaptation cost parameters such as α and θ decrease, technology can be generated through outsourcing because the relative disadvantage of outsourcing in production stage will decrease. For example, as firms base their production on the so-called "science-based" technology, and science becomes more commercializable, this could reduce the adaptation cost in production because scientific knowledge is usually codified and put in public domain. In such an environmental change, firms will shift the source of science-based technologies from their corporate research labs to external sources such as universities and research focused start-ups. This may explain why U.S. corporations have changed their R&D strategy and organizations from in-house, which used to be popular in the postwar ear, to collaboration with universities and other firms. If value *V* of each good increases, the relative cost of adaptation will decrease and thus a firm will purchase technology with broader application from external sources. Lastly, if research cost increases, a firm will buy the technology from the market because the expected research period $1/\lambda_{out}$ is shorter under outsourcing than $1/\lambda_{in}$ under in-house development

4.5. Conclusion

This paper shows that if the adaptation cost relative to market value is large, a firm is likely to develop in-house a technology that has a broad range of applications. In contrast, a firm is likely to purchase a technology with a narrow range of applications from the marketplace. In addition, as the adaptation cost decreases, the value of each application increases and research costs increase, a firm is likely to seek its technological knowledge from the marketplace. Lastly, firms are likely to end up with rapid but narrow-ranged innovation if a technology is purchased from the marketplace.

These results suggest that technology selection and a firm's production flexibility need to be analyzed together, and that the organizational design of research can influence the rate and types of innovations. If industrial innovation impacts the competitiveness and growth of national economy, and if industrial innovation is influenced by how to organize R&D activities, we need to analyze corporate R&D organizations and their positions in the entire production process to understand an important mechanism through which technological change can influence economic growth.

To further examine the relationship between technological change and the organizational design of R&D, we need to explore the following issues:

First, what is the source of the adaptation cost of technology in the manufacturing stage? One source could be the distribution of decision rights between a research division and a manufacturing division regarding technology selection. Because the types of information that each division is gathering are different, who has the decision rights may affect types and rate of innovation. Recent development in corporate research organizations seems to clearly illustrate this point. After discarding the academic-institution-like atmosphere in their corporate labs, the major U.S. corporations have scattered scientists throughout non-research departments such as a manufacturing department and over the whole production process. They also are encouraging communication among researchers and business staff, and incorporating suggestions from non-research business personnel on research projects (Buderi 2000; *the Economist*, March 3, 2007).

Second, how will firms choose the range of applications when they are developing a technology? The range of products to which a new technology will be applied is intrinsically uncertain and complex. Despite this high uncertainty, firms may estimate the possible number of applications when they decide to invest in a new technology. Developing a “platform technology” is a case in point. The platform technology in Honda’s 1990 Accord line could support a number of subsequent process and product changes (Wheelwright and Clark 1992). So, will firms tend to develop this platform technology in-house or purchase it from the marketplace? How will complementarity between applications affect the sourcing decision of a firm? This would be an interesting application of the traditional make-or-buy framework to product development.

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APPENDIX A

Shapley Value Calculation and Proofs of Propositions in Chapter 2

1. Calculation of the Shapley Value under single-tasking

1.1. Cases of possible coalitions

Coalition *S*	$v(S)$	*I*	*#S*	$p(S)$
{ M, 1, 2}	$\min\{a_1, b_2\}$	3	3	$2!/3!$
{M, 1}	0	3	2	$1/3!$
{M,2}	0	3	2	$1/3!$
{1,2}	0	3	2	$1/3!$
{M}	0	3	1	$2!/3!$
{1}	0	3	1	$2!/3!$
{2}	0	3	1	$2!/3!$
ϕ	0	3	0	0

$p(S) = (I - \#S)!(\#S - 1)!/I!,$

$B_i(a,b) = \sum_{S|i \in S} p(S)[v(S\,|\,a,b) - v(S \setminus \{i\}\,|\,a,b)], i = M,1,2$

1.2. Calculation of B_M under single-tasking

Coalition *S*	Contribution $v(S\,|\,e_1,e_2) - v(S \setminus \{i\}\,|\,e_1,e_2)$	$p(S)$	Contribution* $p(S)$

{ M, 1, 2}	$\min\{a_1, b_2\}$	$2!/3!$	$(1/3)\min\{a_1, b_2\}$
{M, 1}	0	$1/3!$	0
{M,2}	0	$1/3!$	0
{M}	0	$2!/3!$	0
B_M	$(1/3)\min\{a_1, b_2\}$		

1.3. Calculation of B_1 under single-tasking

Coalition *S*	Contribution $v(S \mid e_1, e_2) - v(S \setminus \{i\} \mid e_1, e_2)$	$p(S)$	Contribution* $p(S)$
{ M, 1, 2}	$\min\{a_1, b_2\}$	$2!/3!$	$(1/3)\min\{a_1, b_2\}$
{M, 1}	0	$1/3!$	0
{1,2}	0	$1/3!$	0
{1}	0	$2!/3!$	0
B_1	$(1/3)\min\{a_1, b_2\}$		

The Shapley value B_2 of worker 2 can be similarly calculated.

2. Calculation of the Shapley value under multitasking

2.1. Cases of possible coalitions

Coalition *S*	$v(S)$	*I*	*#S*	$p(S)$
{ M, 1, 2}	$\min\{a_1 + a_2, b_1 + b_2\}$	3	3	$2!/3!$
{M, 1}	$\min\{a_1, b_1\}$	3	2	$1/3!$
{M,2}	$\min\{a_2, b_2\}$	3	2	$1/3!$
{1,2}	0	3	2	$1/3!$
{M}	0	3	1	$2!/3!$

{1}	0	3	1	$2!/3!$
{2}	0	3	1	$2!/3!$
ϕ	0	3	0	0

$$p(S) = (I - \#S)!(\#S - 1)!/I!$$

$$B_i(a,b) = \sum_{S|i \in S} p(S)[v(S \mid a,b) - v(S \setminus \{i\} \mid a,b)],\ i = M,1,2$$

2.2. Calculation of B_M under multitasking

Coalition S	Contribution $v(S \mid e_1, e_2) - v(S \setminus \{i\} \mid e_1, e_2)$	$p(S)$	Contribution* $p(S)$
{ M, 1, 2}	$\min\{a_1 + a_2, b_1 + b_2\}$	$2!/3!$	$(1/3)\min\{a_1 + a_2, b_1 + b_2\}$
{M, 1}	$\min\{a_1, b_1\}$	$1/3!$	$(1/6)\min\{a_1, b_1\}$
{M,2}	$\min\{a_2, b_2\}$	$1/3!$	$(1/6)\min\{a_2, b_2\}$
{M}	0	$2!/3!$	0
B_M	$(1/3)\min\{a_1 + a_2, b_1 + b_2\} + (1/6)\min\{a_1, b_1\} + (1/6)\min\{a_2, b_2\}$		

2.3. Calculation of B_1 under multitasking

Coalition S	Contribution $v(S \mid e_1, e_2) - v(S \setminus \{i\} \mid e_1, e_2)$	$p(S)$	Contribution* $p(S)$
{ M, 1, 2}	$\min\{a_1 + a_2, b_1 + b_2\}$ $- \min\{a_2, b_2\}$	$2!/3!$	$(1/3)\min\{a_1 + a_2, b_1 + b_2\}$ $-(1/3)\min\{a_2, b_2\}$
{M, 1}	$\min\{a_1, b_1\}$	$1/3!$	$(1/6)\min\{a_1, b_1\}$
{1,2}	0	$1/3!$	0
{1}	0	$2!/3!$	0
B_1	$(1/3)\min\{a_1 + a_2, b_1 + b_2\} + (1/6)\min\{a_1, b_1\} - (1/3)\min\{a_2, b_2\}$		

2.4. Calculation of B_2 under multitasking

Coalition S	Contribution $v(S \mid e_1, e_2) - v(S \setminus \{i\} \mid e_1, e_2)$	$p(S)$	Contribution* $p(S)$
{ M, 1, 2}	$\min\{a_1 + a_2, b_1 + b_2\}$ $- \min\{a_1, b_1\}$	$2!/3!$	$(1/3)\min\{a_1 + a_2, b_1 + b_2\}$ $-(1/3)\min\{a_1, b_1\}$
{M, 2}	$\min\{a_2, b_2\}$	$1/3!$	$(1/6)\min\{a_2, b_2\}$
{1,2}	0	$1/3!$	0
{2}	0	$2!/3!$	0
B_2	$(1/3)\min\{a_1 + a_2, b_1 + b_2\} + (1/6)\min\{a_2, b_2\} - (1/3)\min\{a_1, b_1\}$		

3. Proof of Proposition 1

The socially optimal production choice is

$$\max_{\{S,M\}}\{\max_{e_1,e_2} TS(e_1, e_2 \mid S), \max_{e_1,e_2} TS(e_1, e_2 \mid M)\}, e_i = (a_i, b_i), i = 1,2$$

and each total surplus is

$$TS(e_1, e_2 \mid S) = \min\{a_1, b_2\} - \frac{1}{2\lambda^2} a_1^2 - \frac{1}{2\lambda^2} b_2^2$$

$$TS(e_1, e_2 \mid M) = \min\{a_1 + a_2, b_1 + b_2\} - \frac{1}{2\lambda^2}\left(a_1^2 + b_1^2\right) - ka_1b_1 - \frac{1}{2\lambda^2}\left(a_2^2 + b_2^2\right) - ka_2b_2 .$$

3.1. $\max_{e_1,e_2} TS(e_1, e_2 \mid S)$

At optimum, $a_1 = b_2$; if $a_1 > b_2$, worker 1 can be better off by reducing a_1

$\therefore TS$ is $a_1 - \frac{1}{2\lambda^2} a_1^2 - \frac{1}{2\lambda^2} a_1^2$

$FOC: 1 - \frac{2}{\lambda^2} a_1 = 0$

$\therefore a_1^* = b_2^* = \frac{\lambda^2}{2}$

$\therefore TS(e_1^*, e_2^* \mid S) = \frac{\lambda^2}{2} - \frac{1}{2\lambda^2}\left(\frac{\lambda^2}{2}\right)^2 - \frac{1}{2\lambda^2}\left(\frac{\lambda^2}{2}\right)^2 = \frac{\lambda^2}{4}$

3.2. $\max_{e_1, e_2} TS(e_1, e_2 \mid M)$

At optimum, $a_1 + a_2 = b_1 + b_2$; if $a_1 + a_2 > b_1 + b_2$, worker i with $a_i > b_i$ can be better off by reducing a_i

$\therefore$ At optimum, $TS(e_1, e_2 \mid M) = a_1 + a_2 - \frac{1}{2\lambda^2}\left(a_1^2 + b_1^2\right) - ka_1b_1 - \frac{1}{2\lambda^2}\left(a_2^2 + b_2^2\right) - ka_2b_2$ with $a_1 + a_2 = b_1 + b_2$

$$\therefore L = a_1 + a_2 - \frac{1}{2\lambda^2}\left(a_1^2 + b_1^2\right) - ka_1b_1 - \frac{1}{2\lambda^2}\left(a_2^2 + b_2^2\right) - ka_2b_2 + l\left(b_1 + b_2 - a_1 - a_2\right)$$

From FOC with respect to $a_i, b_i, l, i = 1, 2$

$$\left.\begin{aligned} a_1 &: 1 - \frac{1}{\lambda^2}a_1 - kb_1 - l = 0 \\ b_1 &: -\frac{1}{\lambda^2}b_1 - ka_1 + l = 0 \end{aligned}\right\} \Rightarrow 1 - \frac{1}{\lambda^2}\left(a_1 + b_1\right) - k\left(a_1 + b_1\right) = 0$$

$$\left.\begin{aligned} a_2 &: 1 - \frac{1}{\lambda^2}a_2 - kb_2 - l = 0 \\ b_2 &: -\frac{1}{\lambda^2}b_2 - ka_2 + l = 0 \end{aligned}\right\} \Rightarrow 1 - \frac{1}{\lambda^2}\left(a_2 + b_2\right) - k\left(a_2 + b_2\right) = 0$$

$l : b_1 + b_2 = a_1 + a_2$

$$\therefore \begin{cases} 1 = \left(\frac{1}{\lambda^2} + k\right)\left(a_1 + b_1\right) \\ 1 = \left(\frac{1}{\lambda^2} + k\right)\left(a_2 + b_2\right) \\ b_1 + b_2 = a_1 + a_2 \end{cases}$$

$$\therefore \begin{cases} a_1 + b_1 = a_2 + b_2 \\ a_1 + a_2 = b_1 + b_2 \end{cases} \text{ and } \begin{cases} a_1 = b_2 \\ b_1 = a_2 \end{cases}$$

$$\therefore \begin{cases} 1 = \left(\frac{1}{\lambda^2} + k\right)\left(a_1 + a_2\right) \\ 1 = \left(\frac{1}{\lambda^2} + k\right)\left(b_1 + b_2\right) \end{cases}$$

From FOCs with respect to $b_i, i = 1, 2$

$$\left.\begin{aligned} b_1 &: -\frac{1}{\lambda^2}b_1 - ka_1 + l = 0 \\ b_2 &: -\frac{1}{\lambda^2}b_2 - ka_2 + l = 0 \end{aligned}\right\} \Rightarrow -\frac{1}{\lambda^2}\left(b_1 + b_2\right) - k\left(a_1 + a_2\right) + 2l = 0$$

$$\therefore \frac{1}{\lambda^2}\left(b_1 + b_2\right) + k\left(a_1 + a_2\right) = 2l$$

$$\therefore \left(\frac{1}{\lambda^2} + k\right)\left(a_1 + a_2\right) = 2l \quad (\because a_1 + a_2 = b_1 + b_2 = \frac{1}{1/\lambda^2 + k})$$

$$\therefore l = \frac{1}{2}$$

From FOCs with respect to $a_i, b_i, i = 1, 2$ and $a_1 = b_2, b_1 = a_2$

$$\left.\begin{aligned} \frac{1}{2} &= \frac{1}{\lambda^2} a_1 + kb_1 \\ \frac{1}{2} &= \frac{1}{\lambda^2} b_1 + ka_1 \end{aligned}\right\} \Rightarrow \left\{\begin{aligned} \frac{1}{2} &= \frac{1}{\lambda^2} b_2 + kb_1 \\ \frac{1}{2} &= \frac{1}{\lambda^2} b_1 + kb_2 \end{aligned}\right. \Rightarrow b_1^* = b_2^* = \frac{\lambda^2}{2\left(1+\lambda^2 k\right)}$$

$$\left.\begin{aligned} \frac{1}{2} &= \frac{1}{\lambda^2} a_2 + kb_2 \\ \frac{1}{2} &= \frac{1}{\lambda^2} b_2 + ka_2 \end{aligned}\right\} \Rightarrow \left\{\begin{aligned} \frac{1}{2} &= \frac{1}{\lambda^2} a_2 + ka_1 \\ \frac{1}{2} &= \frac{1}{\lambda^2} a_1 + ka_2 \end{aligned}\right. \Rightarrow a_1^* = a_2^* = \frac{\lambda^2}{2\left(1+\lambda^2 k\right)}$$

let $a_1^* = b_1^* = a_2^* = b_2^* = \dfrac{\lambda^2}{2\left(1+\lambda^2 k\right)} \equiv d$

$$\therefore TS(e_1^*, e_2^* \mid M) = 2d - \frac{1}{2\lambda^2}2d^2 - kd^2 - \frac{1}{2\lambda^2}2d^2 - kd^2$$

$$= 2d\left[1 - \left(\frac{1}{\lambda^2} + k\right)d\right]$$

$$= 2\left(\frac{\lambda^2}{2\left(1+\lambda^2 k\right)}\right)\left(1 - \frac{1+\lambda^2 k}{\lambda^2}\frac{\lambda^2}{2\left(1+\lambda^2 k\right)}\right)$$

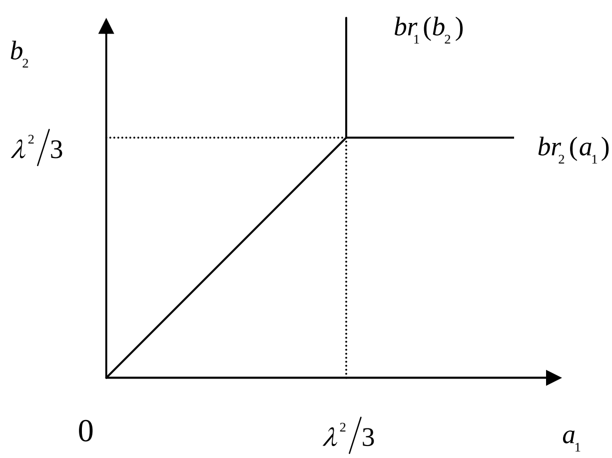
$$= \frac{\lambda^2}{2\left(1+\lambda^2 k\right)}$$

Because $1 > \lambda^2 k$, $TS(e_1^*, e_2^* \mid S) = \dfrac{\lambda^2}{4}$ and $TS(e_1^*, e_2^* \mid M) = \dfrac{\lambda^2}{2\left(1+\lambda^2 k\right)}$ imply multitasking is socially optimal. This proves the proposition 1 (a).

Since, $1 > \lambda^2 k$, $a_1^* = b_2^* = \dfrac{\lambda^2}{2}$ under single-tasking and $a_i^* + b_i^* = \dfrac{\lambda^2}{1+\lambda^2 k}, i = 1, 2$ under multitasking, each worker always makes more total task-specific investments under multitasking than under single-tasking. This proves the proposition 1 (b).

4. Proof of Lemma 1

To prove the first part of lemma, I will examine the best response functions of workers. Given b_2, worker 1 will not exert $a_1 > b_2$ because $U_1 = b_2 - (1/2)(a_1/\lambda)^2$ and then the optimal investment should be zero. When $a_1 \le b_1$, $U_1 = (1/3)a_1 - (1/2)(a_1/\lambda)^2$ and the solution of the first order condition is $\lambda^2/3$. If $b_2 < \lambda^2/3$, the best response $a_1(b_2)$ of worker 1 is b_2. If $b_2 \ge \lambda^2/3$, $a_1(b_2) = \lambda^2/3$. This is the best response function of worker 1. Similarly, the best response function $b_2(a_1)$ of worker 2 will be as follows: If $a_1 < \lambda^2/3, b_2(a_1) = a_1$: If $a_1 \ge \lambda^2/3, b_2(a_1) = \lambda^2/3$. This game has a continuum of Nash equilibria such that $a_1^* = b_2^*$ with a_1^* and b_2^* in $[0, \lambda^2/3]$. The following figure shows the best response functions and these equilibria.



Because the utility of a worker is strictly concave in investment, each worker maximizes his utility at $\lambda^2/3$.

5. Proof of Lemma 2

Suppose $c \equiv b_2 - a_2 \ge 0$ is given. To obtain the best response functions of workers, note that a worker's utility function

$$U_1(e_1, e_2) = 1/3\min\{a_1 + a_2, b_1 + b_2\} + 1/6\min\{a_1, b_1\} - 1/3\min\{a_2, b_2\}$$
$$-[1/2\left(a_1/\lambda\right)^2 + 1/2\left(b_1/\lambda\right)^2 + ka_1b_1]$$

has three different forms over the following ranges of $a_1 - b_1$: (a) $a_1 - b_1 < 0$, (b) $a_1 - b_1 \in [0, c]$, and (c) $a_1 - b_1 > c$. I will show that worker 1's best response cannot be $a_1 - b_1 < 0$ in (a) or $a_1 - b_1 > c$ in (c). Then, I will examine the best response in the region (b).

Case 1) $a_1 - b_1 < 0$. In this range, the utility function is

$$U_1(e_1, e_2) = \left(1/3\right)\left(a_1 + a_2\right) + \left(1/6\right)a_1 - 1/3\,a_2$$
$$-[1/2\left(a_1/\lambda\right)^2 + 1/2\left(b_1/\lambda\right)^2 + ka_1b_1].$$

Suppose worker 1's best response a_1, b_1 is such that $a_1 < b_1$. Because worker 1's utility function has the above form, he can increase his utility by reducing b_1 to $b_1 - \varepsilon$. This contradicts that a_1, b_1 are the best response of worker 1 given $c > 0$. Formally, from the first order condition, the best response of worker 1 is

$$\frac{\delta U_1}{\delta a_1} = \frac{1}{2} - \frac{a_1}{\lambda^2} - kb_1 = 0 \Rightarrow \frac{1}{2} = \frac{a_1}{\lambda^2} + kb_1$$
$$\frac{\delta U_1}{\delta b_1} = -\frac{b_1}{\lambda^2} - ka_1 = 0 \quad \Rightarrow 0 = -\frac{b_1}{\lambda^2} - ka_1.$$

$$\Rightarrow \frac{1}{2} = \frac{\left(a_1 - b_1\right)}{\lambda^2} - k\left(a_1 - b_1\right)$$

$$\Rightarrow \frac{1}{2} = \left(\frac{1}{\lambda^2} - k\right)\left(a_1 - b_1\right)$$

$\therefore \left(a_1 - b_1\right) = \dfrac{1}{2\left(\dfrac{1}{\lambda^2} - k\right)} = \dfrac{\lambda^2}{2\left(1 - \lambda^2 k\right)} > 0$ because $\dfrac{1}{\lambda^2} > k$ from the convex cost function. This contradicts the assumption $a_1 - b_1 < 0$.

Case 3) $a_1 - b_1 > c$. In this range, the utility function is

$$U_1(e_1, e_2) = \left(1/3\right)\left(b_1 + b_2\right) + \left(1/6\right)b_1 - 1/3\,a_2$$
$$-[1/2\left(a_1/\lambda\right)^2 + 1/2\left(b_1/\lambda\right)^2 + ka_1b_1].$$

Suppose worker 1's best response a_1, b_1 is such that $a_1 > b_1 + c$. Because worker 1's utility function has the above form, he can increase his utility by reducing a_1 to $a_1 - \varepsilon$. This contradicts that a_1, b_1 is the best response of worker 1 given $c > 0$. $c > 0$. Formally, from the first order condition, the best response of worker 1 is

$$\frac{\delta U_1}{\delta a_1} = -\frac{a_1}{\lambda^2} - kb_1 = 0 \Rightarrow 0 = -\frac{a_1}{\lambda^2} - kb_1$$
$$\frac{\delta U_1}{\delta b_1} = \frac{1}{2} - \frac{b_1}{\lambda^2} - ka_1 = 0 \quad \Rightarrow \frac{1}{2} = \frac{b_1}{\lambda^2} + ka_1 .$$

$$\Rightarrow \frac{1}{2} = k\left(a_1 - b_1\right) - \frac{\left(a_1 - b_1\right)}{\lambda^2}$$

$$\Rightarrow \frac{1}{2} = \left(k - \frac{1}{\lambda^2}\right)\left(a_1 - b_1\right)$$

$\therefore \left(a_1 - b_1\right) = \dfrac{1}{2\left(k - \dfrac{1}{\lambda^2}\right)} = \dfrac{\lambda^2}{2\left(\lambda^2 k - 1\right)} < 0$ because $\dfrac{1}{\lambda^2} > k$ from the convex cost function. This contradicts the assumption $a_1 - b_1 > c > 0$.

Case 2) $a_1 - b_1 \in [0, c]$. In this range, the utility function is

$$U_1(e_1, e_2) = \left(1/3\right)\left(a_1 + a_2\right) + \left(1/6\right)b_1 - 1/3\, a_2$$
$$- [1/2\left(a_1/\lambda\right)^2 + 1/2\left(b_1/\lambda\right)^2 + ka_1b_1] .$$

From the first order condition, worker 1's best response will satisfy

$$\frac{\delta U_1}{\delta a_1} = \frac{1}{3} - \frac{a_1}{\lambda^2} - kb_1 = 0 \Rightarrow \frac{1}{3} = \frac{a_1}{\lambda^2} + kb_1$$
$$\frac{\delta U_1}{\delta b_1} = \frac{1}{6} - \frac{b_1}{\lambda^2} - ka_1 = 0 \quad \Rightarrow -\frac{1}{6} = -\frac{b_1}{\lambda^2} - ka_1$$

$$\Rightarrow \frac{1}{6} = \frac{\left(a_1 - b_1\right)}{\lambda^2} - k\left(a_1 - b_1\right)$$

$$\Rightarrow \frac{1}{6} = \left(\frac{1}{\lambda^2} - k\right)\left(a_1 - b_1\right)$$

$\therefore (a_1 - b_1) = \frac{1}{6\left(\frac{1}{\lambda^2} - k\right)} = \frac{\lambda^2}{6(1-\lambda^2 k)} > 0$ because $\frac{1}{\lambda^2} > k$ from the convex cost function. Therefore, this implies that the best response of worker 1 can exist when $a_1 - b_1 \in [0, c]$. If $\lambda^2 / 6(1-\lambda^2 k) \le c$, $a_1 - b_2 = \lambda^2 / 6(1-\lambda^2 k)$. If $\lambda^2 / 6(1-\lambda^2 k) > c$, $a_1 - b_1 = c$. This characterizes the best response of worker 1 as $a_1 - b_1 = \text{constant } K$. Then, substituting $b_1 + K$ for a_1 in the utility function,

$$U_1(e_1, e_2) = (1/3)(b_1 + K + a_2) + (1/6)b_1 - 1/3\, a_2 \\ - [1/2((b_1 + K)/\lambda)^2 + 1/2(b_1/\lambda)^2 + k(b_1 + K)b_1].$$

From the first order condition,

$$\frac{\delta U_1}{\delta b_1} = \frac{1}{2} - \frac{1}{2\lambda^2}[2(b_1 + K) + 2b_1] - k[b_1 + b_1 + K] = 0$$

$$\Rightarrow \frac{1}{2} - \frac{1}{\lambda^2}[2b_1 + K] - k[2b_1 + K] = 0$$

$$\Rightarrow \frac{1}{2} = \left(\frac{1}{\lambda^2} + k\right)[2b_1 + K]$$

$$\therefore b_1 = \frac{1}{4(1/\lambda^2) + k} - \frac{K}{2} \text{ and } a_1 = \frac{1}{4(1/\lambda^2) + k} + \frac{K}{2} \text{ where } K \equiv \min\{c, \frac{\lambda^2}{6(1-\lambda^2 k)}\}.$$

Similarly, worker 2' best response is as follows: $b_2 = \frac{1}{4(1/\lambda^2) + k} + \frac{K}{2}$ and $a_1 = \frac{1}{4(1/\lambda^2) + k} - \frac{K}{2}$ where $K \equiv \min\{c', \frac{\lambda^2}{6(1-\lambda^2 k)}\}$ with $c' \equiv a_1 - b_1$. Suppose worker 2 exerts a_2 and b_2 such that $b_2 - a_2 > \lambda^2 / 6(1-\lambda^2 k)$. Then, the best response of worker 1 is such that $a_1 - b_1 = \lambda^2 / 6(1-\lambda^2 k)$. However, given $a_1 - b_1 = \lambda^2 / 6(1-\lambda^2 k)$, a_2, b_2 such that $b_2 - a_2 > \lambda^2 / 6(1-\lambda^2 k)$ is not worker 2's best response. Therefore, at equilibrium, $a_1 + a_2 = b_1 + b_2$.

To prove that $a_i = b_i, i = 1, 2$ at the best equilibrium, suppose $a_1 > b_1$ and $a_2 < b_2$ at the best equilibrium. Because $a_1 + a_2 = b_1 + b_2$, and the utilities of worker 1and 2 are

$$U_1(e_1, e_2) = 1/3\,\text{constant} + 1/6\, b_1 - 1/3\, a_2 - [1/2(a_1/\lambda)^2 + 1/2(b_1/\lambda)^2 + k a_1 b_1],$$

$$U_2(e_1,e_2) = 1/3\,\text{constant} + 1/6\,a_2 - 1/3\,b_1 - [1/2\left(a_2/\lambda\right)^2 + 1/2\left(b_2/\lambda\right)^2 + ka_2b_2]$$

worker 1 and worker 2 can increase their utility by reducing a_1 to $a_1 - \varepsilon$ and b_2 to $b_2 - \varepsilon$, respectively. This contradicts that $a_1 > b_1$ and $a_2 < b_2$ at the best equilibrium.

6. Proof of Lemma 3

Let F_o be $\left[\lambda^2/4(1+\lambda^2 k)\right] - \lambda^2/9$. Because $\lambda^2 k < 1$, F_o >0. Moreover, $\pi_M = \pi_S$ at F_o , Thus, the manager chooses multitasking if and only if $F \le F_o$

7. Proof of Lemma 4

Because $F_0 = \left[\lambda^2/4(1+\lambda^2 k)\right] - \lambda^2/9$,

$$\frac{\partial F_o}{\partial k} = \frac{-4\lambda^2}{[4(1+\lambda^2 k)]^2} < 0$$

$$\frac{\partial F_o}{\partial \lambda^2} = \left[\frac{1}{4(1+\lambda^2 k)} - \frac{1}{9}\right] + \lambda^2\left[\frac{-4k}{\left[4(1+\lambda^2 k)\right]^2}\right]$$

$$= \frac{9 - 4(1+\lambda^2 k)^2}{36(1+\lambda^2 k)^2}$$

Thus, $\frac{\partial F_o}{\partial \lambda^2} \ge 0$ if and only if $9 - 4(1+\lambda^2 k)^2 \ge 0$. This condition holds if and only if $\lambda^2 k \le 1/2$. Therefore,

$$\frac{\partial F_o}{\partial \lambda^2} \ge 0 \text{ if } \lambda^2 k \le 1/2$$
$$\frac{\partial F_o}{\partial \lambda^2} < 0 \text{ if } 1/2 < \lambda^2 k < 1 .$$

8. Proof of Proposition 3

Proof of (a). Because the manager has chosen multitasking, $F \in [F_L, F_o]$ where $F_o = \left[\lambda^2/4(1+\lambda^2 k)\right] - \lambda^2/9$. From the best equilibrium outcome, the ratio R_M of profit to total wage bill is

$$R_M = \frac{\lambda^2 / 4(1+\lambda^2 k) - F}{\lambda^2 / 4(1+\lambda^2 k)} \text{ where } F \in [F_L, F_o].$$

Thus, the lower bound *lb* of R_M is $4(1+\lambda^2 k)/9$, which is attained at $F = F_o$, and its upper bound is one. From the result that the ratio R_S under single-tasking is $1/2$, we need to compare this lower bound with $1/2$. Thus,

$$1/2 \le lb \text{ for } \forall F \in [F_L, F_0] \text{ if } \lambda^2 k \ge 1/8.$$

Proof of (b) and (c). Suppose that $\lambda^2 k < 1/8$. Then, $4/9 < lb < 1/2$. Let F_1 be F such that $R_M = R_S = 1/2$.

$$\frac{\lambda^2 / 4(1+\lambda^2 k) - F_1}{\lambda^2 / 4(1+\lambda^2 k)} = \frac{1}{2}$$

$$\therefore F_1 = \frac{\lambda^2}{8(1+\lambda^2 k)} > 0$$

And $F_1 < F_o$ because

$$F_o - F_1 = \left[\frac{\lambda^2}{4(1+\lambda^2 k)} - \frac{\lambda^2}{9}\right] - \frac{\lambda^2}{8(1+\lambda^2 k)}$$

$$= \frac{\lambda^2}{8(1+\lambda^2 k)} - \frac{\lambda^2}{9}$$

$$> 0 \qquad \text{since } \lambda^2 k < \frac{1}{8}$$

Therefore, $R_M \ge R_S$ if $F_L \le F \le F_1$ and $R_M < R_S$ if $F_1 < F \le F_o$.

9. Proof of Proposition 4

From $P_S(e_1^*, e_2^*) = \lambda^2/3, g_i(e_i^* \mid S) = \left(1/2\lambda^2\right)\left(\lambda^2/3\right)^2 = \lambda^2/18$,

$TS(e_1^*, e_2^* \mid S) = P_S(e_1^*, e_2^*) - g_1(e_1^* \mid S) - g_2(e_2^* \mid S)$

$= \lambda^2/3 - 2 * \lambda^2/18 = 2\lambda^2/9$

From $P_M(e_1^*, e_2^*) = \lambda^2 \big/ 2\left(1+\lambda^2 k\right)$ and

$g_i(e_i^* \mid M) = \left(1/2\lambda^2\right)\left(a_i^{*2} + b_i^{*2}\right) + k a_i^* b_i^* = \left(1/\lambda^2 + k\right) a_i^{*2}$

$= \left(\left(1+\lambda^2 k\right)\big/\lambda^2\right)\left(\lambda^2 \big/ 4\left(1+\lambda^2 k\right)\right)^2 = \lambda^2 \big/ 16\left(1+\lambda^2 k\right),$

$\left(\because a_i^* = b_i^* = \lambda^2 \big/ 4\left(1+\lambda^2 k\right)\right)$

$TS(e_1^*, e_2^* \mid M) = P_M(e_1^*, e_2^*) - g_1(e_1^* \mid M) - g(e_2^* \mid M)$

$= \lambda^2 \big/ 2\left(1+\lambda^2 k\right) - 2 * \lambda^2 \big/ 16\left(1+\lambda^2 k\right) = (3/8)\left(\lambda^2 \big/ \left(1+\lambda^2 k\right)\right)$

Here direct comparison of $TS(e_1^*, e_2^* \mid S) = 2\lambda^2/9$ and $TS(e_1^*, e_2^* \mid M) = (3/8)\left(\lambda^2 \big/ \left(1+\lambda^2 k\right)\right)$ proves proposition 4.

APPENDIX B

Proofs of Propositions in Chapter 3

1. Proof of Proposition 5

The researcher will submit if $pb_{pub} - I_{pub} \geq q(\phi)b_{pat} - I_{pat}$ and apply otherwise . Thus, he submits if $\frac{pb_{pub} - I_{pub} + I_{pat}}{b_{pat}} \geq q(\phi)$ and applyies otherwise . Let ϕ_{no} be such that $\frac{pb_{pub} - I_{pub} + I_{pat}}{b_{pat}} = q(\phi_{no})$. Then, the researcher submits for publication if $\phi \leq \phi_{no}$ and applies for patent if $\phi > \phi_{no}$ □

2. Proof of Proposition 6

(a) Given journal submission, if the manager confirms, she will get pB_{pub}. If she directs to change, she will get $q(\phi)B_{pat}$. Thus, confirm $\succ$ direct *iff* $pB_{pub} \succ q(\phi)B_{pat}$. Let $\phi_M \in (0,1)$ be such that $q(\phi_M) = p\frac{B_{pub}}{B_{pat}}$. Since q is increasing, confirm $\succ$ direct *iff* $\phi_M > \phi$. Thus, if research stage is sufficiently basic ($\phi_M > \phi$), the manager confirms the researcher's journal submission. If research stage is sufficiently applied ($\phi_M < \phi$), the manager directs to apply for patent. Given patent application, if the manager confirms, she will get $q(\phi)B_{pat}$, and pB_{pub} otherwise. Thus, confirm $\succ$ direct *iff* $q(\phi)B_{pat} \succ pB_{pub}$ *iff* $\phi > \phi_M$, where ϕ_M *s.t.* $q(\phi_M) = p\frac{B_{pub}}{B_{pat}}$. Thus, if research is sufficiently applied, the manager confirms the patent application and directs to change otherwise. Given this strategy of the manager, consider the researcher's optimal strategy. Suppose $\phi \le \phi_M$. If he submits to the journal, his expected utility will be $pb_{pub} - I_{pub}$. If he submits to the journal, his expected utility will be $pb_{pub} - I_{pub} - \varepsilon$. Thus, the researcher's optimal strategy is to submit to the journal if research state is sufficiently basic. Let's suppose that $\phi > \phi_M$. If the researcher chooses to publish, he will get $q(\phi)b_{pat} - I_{pat} - \varepsilon$. If he applies for patent, his expected utility is $q(\phi)b_{pat} - I_{pat}$. Thus, his optimal strategy when $\phi > \phi_M$ is to patent.

(b) From proposition 1 and 2, ϕ_{no}, ϕ_M are such that $q(\phi_{no}) = \dfrac{pb_{pub} - I_{pub} + I_{pat}}{b_{pat}}$ and $q(\phi_M) = p\dfrac{B_{pub}}{B_{pat}}$. Suppose that $I_{pat} = I_{pub}$ and $(b_{pub}/b_{pat}) > (B_{pub}/B_{pat})$ because researchers care about publication more than do managers. Then, $q(\phi_M) < q(\phi_{no})$. This implies $\phi_M < \phi_{no}$ because q is increasing. □

APPENDIX C

Proofs of Propositions in Chapter 4

1. Proof of Proposition 7

The difference between $\Pi(in-house)$ and $\Pi(outsourcing)$ is

$$\begin{aligned}&\Pi(in-house)-\Pi(outsourcing)\\&=\delta^{1/\lambda_{in}}\left(nV-n\alpha-r/\lambda_{in}\right)-\delta^{1/\lambda_{out}}\left(nV-n\theta\alpha-r/\lambda_{out}\right)\\&=n[\delta^{1/\lambda_{in}}(V-\alpha)-\delta^{1/\lambda_{out}}(V-\theta\alpha)]-r[\delta^{1/\lambda_{in}}\left(1/\lambda_{in}\right)-\delta^{1/\lambda_{out}}\left(1/\lambda_{out}\right)]\end{aligned}.$$

Let n^* be such that $n^*[\delta^{1/\lambda_{in}}(V-\alpha)-\delta^{1/\lambda_{out}}(V-\theta\alpha)]=r[\delta^{1/\lambda_{in}}\left(1/\lambda_{in}\right)-\delta^{1/\lambda_{out}}\left(1/\lambda_{out}\right)]$ .If $\alpha/V>\left(\delta^{1/\lambda_{out}}-\delta^{1/\lambda_{in}}\right)/\left(\theta\delta^{1/\lambda_{out}}-\delta^{1/\lambda_{in}}\right)$, then $\delta^{1/\lambda_{in}}(V-\alpha)-\delta^{1/\lambda_{out}}(V-\theta\alpha)>0$. Thus, if $\delta^{1/\lambda_{in}}\left(1/\lambda_{in}\right)>\delta^{1/\lambda_{out}}\left(1/\lambda_{out}\right)$, then $n>n^*$ iff $\pi(in-house)>\pi(outsourcing)$ and n^* is strictly positive. □

2. Proof of Proposition 8

Note that $n^*[(\theta\delta^{1/\lambda_{out}}-\delta^{1/\lambda_{in}})\alpha-(\delta^{1/\lambda_{out}}-\delta^{1/\lambda_{in}})V]=r[\delta^{1/\lambda_{in}}\left(1/\lambda_{in}\right)-\delta^{1/\lambda_{out}}\left(1/\lambda_{out}\right)]$. If adaptation cost α decreases, n^* will increase because $(\theta\delta^{1/\lambda_{out}}-\delta^{1/\lambda_{in}})\alpha-(\delta^{1/\lambda_{out}}-\delta^{1/\lambda_{in}})V$ will decrease. The same logic will be applied to the increase in θ. These prove (a) and (b). If value V increases, n^* will increase because $(\theta\delta^{1/\lambda_{out}} - \delta^{1/\lambda_{in}})\alpha - (\delta^{1/\lambda_{out}} - \delta^{1/\lambda_{in}})V$ will decrease. This proves (c). If research cost r increases, n^* will increase because $r[\delta^{1/\lambda_{in}}(1/\lambda_{in}) - \delta^{1/\lambda_{out}}(1/\lambda_{out})]$ will increase. This proves (d). □