Contracting for Employee and Supplier Capability Development

by

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ABSTRACT

This thesis explores the types of capabilities individuals choose to develop, proprietary or general purpose, within an employment relationship. This work is part of a broader effort to examine the processes by which skills are created and deployed within firms and along a supply chain, focusing particularly on helping firms design employment and supply systems which create and capture knowledge to the firm's advantage. Two models and a data set are presented. The first model assumes that individuals are constrained in the amount they can learn each period while the second model allows for unlimited learning at increasing costs. A data set collected from individual respondents at eight firms is used to test model-driven hypotheses and to explore factors affecting capability development that are not explicitly modeled. The data offer greater support for the unconstrained learning model. The models in this thesis contribute to the literature by making reservation wages endogenous and technology dependent.

Thesis Supervisor: Charles H. Fine
Title: Professor of Management Science
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I appreciatively acknowledge the participation of eight firms and their employees in the empirical component of this thesis.

Finally, I am very grateful to Charles Fine, Robert Gibbons, and Morris Cohen for serving as my thesis advisory committee.
DEDICATION

I dedicate this thesis to the memory of my mother

Mary Lynn Goodrich Parker
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1. INTRODUCTION

GENERAL PROBLEM: BUILDING CAPABILITIES ALONG A SUPPLY CHAIN

The aim of this research is to explore the evolution of firm and individual capabilities in supply chains by examining the sequence of customer-supplier contracts, project-by-project, among the members of the chain. This work is motivated by a desire to better understand the process by which skills are created and deployed along a supply chain. The goals are to help firms decide what types of relationships to build with their suppliers and to help suppliers decide which projects to pursue and which firms to work with.

As firms work to design their supply chains, they build relationships with providers of goods, technology, and skills, both within and outside company boundaries. In this work, think of a supply chain as a chain of skills or capabilities superimposed on a chain of organizations (Fine 1996, 1998). This study focuses on skill development, taking as given that the types and strengths of capabilities in the chain are key determinants of supply chain performance. Skills often take substantial time to build, are not easily bound to any one firm, and exhibit interaction effects such that a given skill set may be more productive when combined with one firm's technology than another. Firms which are superior at accumulating, deploying, and contracting for skills can earn profits on these capabilities.

The question for firms is how to contract for a coherent sequence of projects that satisfies the need to compete successfully in today's marketplace and builds a set of desired capabilities to enable competition in tomorrow's marketplace. Supplier capabilities do not remain static over time, but instead constantly evolve as unused capabilities shrink and new capabilities are
created (Leonard-Barton, 1992). Contracting firms must take into account that suppliers will evaluate business opportunities in part by assessing how projects will improve market opportunities outside the existing relationship. The tension is that buyer firms may prefer projects that add little value to a supplier's outside opportunities, but create substantial value within the firm/supplier relationship.

RELATIONSHIP TO OPERATIONS MANAGEMENT

A large literature on supply chain management focuses primarily on logistics and network design, (Buzacott and Shanthikumar, 1992), production, inventory control in multi-echelon systems (Hadley and Whitin, 1963; Hax and Candea, 1984; Schwarz, 1981), and supplier management (Lee et al., 1994). This literature has achieved substantial success in explaining the flow of products along the manufacturing and distribution system that represents a supply chain. Extensive models of production and inventory systems have been developed and deployed in industrial settings. In contrast, the subject of supply chain design has received less attention, although Fine (1996), Fine and Whitney (1996), and Anderson, Fine, and Parker (1996) have explored it to some degree.

Supply chain design is considered here as paramount. It was learned in the last decade that the competence of a firm's suppliers is a key determinant of firm performance (Cusumano and Takeishi, 1991; Nishiguchi, 1994). It was also learned that the high leverage point for improving manufacturing is often the product design process rather than the factory (Nevins and Whitney, 1989; Whitney, 1988). Similarly, Fine (1998) posits a supply chain design approach whereby supply chain performance may be most influenced by decisions made at the design stage rather than in the management of ongoing production, inventory, and logistics issues in an already-operating
supply chain. The interest in this paper is to consider ongoing capability development as one aspect of supply chain design and development. The key is to determine what kinds of suppliers (high skill -- low skill) to work with and what types of relationships (vertical-integration -- long-term contract -- spot-market) to build with those suppliers.

This paper builds upon the tactical tradition of the operations management field, but is focused on the strategic design of supply chains. A Harvard Business School case, Fabtek, helps to draw the distinction.¹

**Fabtek example**

The Fabtek case is taught at some business schools jointly between the marketing and operations management departments. This case features a company which specializes in titanium welding. In the case, the company is considering which of four customer orders to accept. Each order places a unique combination of demands upon the firm’s already heavily loaded production facilities and there is nowhere near enough capacity to accept all of the orders. The goal is to figure out which orders the firm should accept.

**Supply chain management - schedule by $/scarce resource (Goldratt)**

One “answer” to the case calculates the contribution/order/unit of scarce resource. This method searches through the orders and accepts the feasible combination that maximizes additional profit. There are analytic tools, especially linear programming, that are especially well suited to solving this type of problem.

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¹ Fabtek(A) - Case # 9-592-095, Harvard Business School, 1992. Morris Cohen brought this example to my attention.
Supply chain design - create systems which build capabilities over time

One longer range analysis of Fabtek's problem looks at the capabilities that might be generated in the process of completing each of the orders the firm might accept. If the project adds no new capabilities, then loading by scarce resource makes the most sense. However, if there are learning implications to each project, then the firm might choose to consider these in its long term analysis. The work presented in this paper attempts to establish some of the building blocks for understanding the strategic implications of projects between customers and suppliers that involve learning.

PROJECT AS UNIT OF ANALYSIS

Much work organized on project basis
The mechanism for building skills examined in this study is the execution and completion of projects. Projects are among the most important mechanisms through which capabilities are generated within individuals and organizations. Examples include the development of a software product (e.g. Cusumano, 1995), the development of an automobile model (e.g. Clark et al. 1987; Clark, 1989), the improvement of a production process (e.g. Shiba et al. 1993), or the construction of a building. Important features of projects are that they are executed by teams of individuals, often from multiple organizations (e.g. in a supply chain), that they have well-defined beginnings and ends, and that they are often the object of contractual negotiations.

Technological re-contracting point
Much of the literature on firm/employee incentive systems has focused on jobs in settings such as manufacturing assembly that may be indefinite in duration. In such instances, the point at which firms and employees negotiate rewards and new assignments may be somewhat arbitrary, or at
least may not be determined by any features inherent in the job or technology. In contrast, the completion of a project provides a technologically driven endpoint for the re-assessment of the employment or supply chain relationship. At that point, the measures of project output upon which rewards might be based should be most readily measured and observed.

**Firms “hiring” suppliers project-by-project**

As many firms seek greater flexibility to match their production capabilities to rapidly changing market demands, they are contracting for more suppliers on a project-by-project basis. This is true for both supplier firms and for individuals. In the software industry, it is common to only hire individuals for the duration of a project. This trend reinforces the need to understand how the choice of projects are agreed upon between firms and suppliers.

**KEY FACTORS IN BUILDING CAPABILITIES**

The negotiation between firms and suppliers over which projects to undertake and how to distribute rewards takes place in a complex setting which includes but is not limited to the following:

**Firm technology**

A major factor that both parties will take into account is the type of technology employed by the firm with which the supplier (firm or individual) must integrate in order to produce the desired output. If the firm employs very specialized technologies, the supplier (if it hasn’t already) will have to acquire the ability to work with this technology. To the extent that the technology is unique, the supplier cannot use the capabilities with other firms, and suppliers will take this into account before agreeing to develop the

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2 "High-Tech Nomads Write New Program For Future of Work ... They move from project to
capability. Suppliers might fear that they will be locked in to a specific technology and that once locked in, they might lose negotiating leverage with the customer firm. If a firm employs general purpose technologies, the capabilities a supplier acquires can be used with other firms.

**Environment**

**Availability of capable supplier base**
If there are a large number of suppliers with the capability set a firm is looking for, then the suppliers will be in a poor negotiating position. This study assumes that the capabilities the firm is contracting for are relatively rare and that the suppliers have market power. This assumption is a departure from much of the literature that assumes a competitive market for supplier capabilities.

**Rate of technological change**
The rate of technological change is a factor that affects the willingness of suppliers to adopt unique capabilities. For example, suppliers to a coal-fired electric generating plant can be confident that the capabilities they develop will likely be useful over the (thirty-to-forty-year) lifetime of the plant. However, the capabilities of suppliers to a consumer electronics firm may obsolesce in a very short time period of years to months. Planning to make capability investments in a rapidly changing environment requires the parties to make the additional calculation of how long the capability is expected to be relevant. The terminology “slow clockspeed” and “fast clockspeed” is used to describe industries that are innovating slowly versus those which are innovating rapidly (Fine, 1998).
Incentives
This study assumes that chain partners act in their own self-interest. That is, suppliers cannot be compelled to undertake projects that are not in their interest. It is assumed that suppliers always have the option to make (potentially unobserved) capability investments in more general technologies if the customer firm does not offer a sufficiently broad set of project choices. Firms must therefore offer incentives to suppliers if they wish suppliers to risk getting locked in to highly unique technologies.

Supply chain design matters: IBM example
IBM's supply chain design decision for the personal computer product line launched in the early 1980s provides an example of the importance of the supplier decisions companies make early in product introductions. At the time, no one had a believable prediction for how large the market for personal computers was going to become. "Heavy Iron," the large mainframe computers upon which IBM was built remained supreme.

Supply chain decision allowed quick entry
IBM tasked Microsoft with the development of the operating system and assigned microprocessor production to Intel. This division of responsibility allowed IBM to gain quick access to the market. The product design and distribution activities carried out by IBM provided the most value added early in the industry life-cycle. However, as other competitors entered the market over time, product designs became standardized and additional distribution channels were developed. IBM was no longer able to earn substantial profits on the basis of these activities.
Supply chain partners appropriate the profit
Fast forward to 1997 and the environment is far different. Both Microsoft and Intel are among the world’s most valuable companies, as measured by market capitalization, each exceeding the market value of IBM by substantial margins in the past two years.\(^3\) As it turned out, the design and sale of personal computer boxes became a commodity business, while the majority of industry profit is made further up the supply chain in microprocessors and operating systems; a recent report said that Intel and Microsoft together earn fully half of the total profits earned in the personal computer industry.\(^4\)

Other firms learned to use Intel/Microsoft output.
Early in the personal computer industry life-cycle, there was a very limited market for Intel and Microsoft output, so IBM could appropriate industry profits. However, other firms developed the capability to manufacture PCs using Intel and Microsoft output. In this way, the capabilities developed by Intel and Microsoft became general to the industry instead of specific to IBM.

Could IBM have done anything differently when it was designing the supply system for the personal computer to capture more of the value created by the capabilities developed along the supply chain? Was there a way of thinking about the supply chain and how the locus of relative value could shift, which might have led IBM to make different decisions about control over personal computer components? Should (could?) IBM have attempted to bind supply chain members to technologies controlled by IBM as opposed to opening the architecture for component by component competition?\(^5\) It is unlikely that the industry would have grown nearly so rapidly if IBM had adopted a closed architecture (as Apple did), forcing Intel and Microsoft to remain captive suppliers. So, any answers to the questions above must take into account the

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desire to create a large and growing market, while at the same time attempting to earn profits from participating in this market.

Another example moves to the realm of an individual worker negotiating over projects within an existing employment relationship. This example forms the starting point for the modeling efforts presented here.

**Skill Retention Matters - Microsoft Programmer Example**

Consider the following hypothetical example. A Microsoft programmer who just completed the latest version of Microsoft Word (a popular multi-platform word-processing program) could have the choice between working on the next version of Word, or the next version of Internet Explorer (an Internet web browser program). By working on the Word project, the programmer would deepen an already extensive knowledge base about designing word-processing programs to work well with other Microsoft applications – a skill that is particularly useful at Microsoft, but of less value elsewhere. In contrast, if the programmer worked on the Internet Explorer project, she would have to learn networking, data transmission, and open document interface standards and protocols. With the explosive growth of Internet applications, the skills for internet experts are in high demand at many companies. If Microsoft offered the programmer the choice, the company would have to make the internally oriented Word project worth the sacrifice the programmer was making by not raising her market value through learning network skills. Microsoft currently makes far more money on proprietary packages like Word and Office than from give-away internet packages. So, the company should have more profit to compensate the programmer for lost learning should she choose the Word project. Both

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5 See Farrell et al. (1994) discussion of closed system versus open component competition.
Microsoft and the programmer should be aware of the knowledge impact of either project choice.

With this example in mind, two models of project choice and learning are analyzed in chapters 3 and 4 respectively.

**TWO PROJECT CHOICE AND LEARNING MODELS**

**Learning constrained individual project choice model**
Chapter 3 presents the restricted learning case where a single firm and a single individual negotiate learning and payments over two periods. This case applies to smaller firms and individuals who cannot rapidly (if at all) increase their technological capabilities.

Several key assumptions drive results in this model. The first is that individuals cannot learn more than a fixed amount in any period; the second is that projects differ mostly in the type of learning opportunities they present, not in the amount of learning. That is, individuals are operating on a learning frontier in each project period. The third is that there is excess demand for the individual’s services. There is a competitor firm willing to pay up to its entire incremental output to gain the services of the individual. Finally, incremental output at the firm is dependent upon the interaction of firm technology and the individual’s capabilities. Incremental output at the competitor firm (in the event the individual leaves to work for the competitor) is also dependent upon the interaction of its technology and the individual’s capabilities.

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6 This example is offered only for illustration and does not reflect an actual situation.
From these assumptions, it is predicted that individuals will align their learning with their employer’s technologies. However, the presence of a competitor with strong general technologies leads individuals to shift their learning toward general technology and away from firm-specific learning. The model also predicts that individuals increase (decrease) their firm-specific (general) learning as firms increase the level of sharing incentives.

**Unconstrained supplier project choice model**

The second model (Chapter 4) considers a supplier of capabilities who has unlimited learning capacity in each period. In order to derive solutions to the supplier’s project choice problem, assume an increasing cost to learning in each period. The other assumptions are shared across both models.

The unconstrained model again predicts that individuals will align their learning with the technologies used by their employer. However, an increase in firm-specific capability does not mean an automatic decrease in general capability as predicted in the constrained model. So, the presence of a competitor with strong general technology leads to an increase in general capability investment by the individual, but does not also lead that individual to reduce firm-specific learning. Another departure from the constrained model is that the unconstrained model predicts, given a threshold value of firm general technology, that general learning rises with sharing incentives.

The contribution of these models is to make reservation wages endogenous and dependent upon firm and industry technology. Individuals (suppliers) can affect their reservation wages through their choice of learning in each period. Firms should be aware of this and can consider the impact of their sharing policies on the alignment of individuals’ interests with the firm’s interests.
PROJECT CHOICE AND LEARNING SURVEY DATA

A data set to explore project choice among technology professionals has been collected from 8 firms in the software, electronics, consulting, and space hardware industries. Scientists, engineers, and programmers at these firms were asked to evaluate how much they learn from their projects and whether that learning is generally applicable or specific to the firm in which they are employed. They were also asked a series of questions about project performance, incentives, motivation, industry experience, and personal background. Relationships between these variables are explored and tested against predictions derived from the models in Chapters 3 and 4.

Analysis of the data tends to support the majority of the hypotheses derived from one model or the other. Where predictions from the constrained learning model diverged from the unconstrained model, the data tend to support the unconstrained model. This is interesting since the data set is comprised of responses from individuals. It would appear that the learning assumptions of the constrained model are called into question.

At the firm level, employees in industries expected to employ mostly general skills (consulting, network software) do in fact report their learning to be more general than individuals who work for specialized firms (space technology, government contracting, medical technology). Workers at firms where the alternate job prospects are expected to be lower report that their employers use fewer sharing incentives than workers at firms in the network software and electronics industries where workers are in high demand. These results are encouraging because they offer evidence that the incentive and learning measures in the data set are consistent with expectations.
Chapter 2 briefly reviews some of the research regarding supply chains, incentives, human capital, organizational learning, and the resource-based view of the firm upon which the models of project choice are based. Chapter 3 presents the learning constrained project choice model. The unconstrained model is developed in Chapter 4. Chapter 5 presents results from the empirical study of project choice and learning. Chapter 6 discusses the implications of this work and Chapter 7 proposes a research agenda to build upon the work.
2. RELATED LITERATURE

The work in this dissertation builds on several different streams of research including supply chains, the resource-based view of the firm, human capital theory, organizational learning, and incentives/contracting. Each of these is sketched briefly below.

SUPPLY CHAINS

Supply chains have been increasingly popular as a subject of study in recent years. A closer look reveals that most literature on supply chain management focuses primarily on logistics and network design, (Buzacott & Shanthikumar, 1992), production, inventory control in multi-echelon systems (Hadley and Whitin, 1963; Hax and Candea, 1984; Schwarz, 1981), and supplier management (Lee et al., 1994). This literature has achieved substantial success in explaining the flow of products along the manufacturing and distribution system that represents a supply chain. Extensive models of production and inventory systems have been developed and deployed in industrial settings. In contrast, the subject of supply chain design has received significantly less attention, although Fine (1996), Fine and Whitney (1996), and Anderson, Fine, and Parker (1996) have explored it to some degree.

Supply chain design is considered here as paramount. In the last decade, the importance of the competence of a firm's suppliers as a key determinant of firm performance became apparent (Cusumano and Takeishi, 1991; Nishiguchi, 1994). It was also learned (Nevins and Whitney, 1989; Whitney, 1988) that the high leverage point for improving manufacturing is often the product design process rather than the factory. Similarly, Fine (1997) posits a
supply chain design approach whereby supply chain performance may be most influenced by decisions made at the design stage rather than in the management of ongoing production, inventory, and logistics issues in an already-operating supply chain. The interest in this paper is to consider ongoing capability development as one aspect of supply chain design and development. The key is to determine what kinds of suppliers (high skill -- low skill) to work with and what types of relationships (vertical-integration -- long-term contract -- spot-market) to build with those suppliers.

Supplier Management
Supplier management has been a key theme of industry research for at least the past fifteen years. It is argued above that firms compete as much on their ability to assemble competent supply chains as they do on any internal competence they have assembled. Older research emphasized adversarial, zero-sum game relationships with suppliers (Porter, 1980). In this spirit, a Chrysler executive recently described the way his firm treated suppliers in the 1970s as “industrial thuggery.”

Much industry research in the 1980s focused on the automobile industry. One major conclusion of this research was that Japanese automobile assembly firms were substantially more capable in their dealings with suppliers than U.S. automobile assembly firms (Clark and Fujimoto, 1991; Womack, Jones, and Roos, 1990). A view of cooperative relationships with suppliers began to emerge as a competitive advantage for Japanese corporations, with one author (Dyer, 1996) claiming that U.S. one U.S. automobile company, Chrysler, has surpassed the Japanese model in some respects. Asanuma (1989) described how supplier firms are developed from providers of off-the-shelf parts to fully integrated suppliers of proprietary technology. It is this process of specialized technology development in the supply base which is of

7 John Maple, presentation at MIT Industry Conference, "Creating and Managing Corporate
particular interest in this dissertation. The next section of this chapter explores the history of the resource-base view of the firm.

**RESOURCE-BASE VIEW OF THE FIRM**

The resource-based view of the firm has received much attention in the general business press in recent years. The basic idea is that firms are comprised of a collection of resources -- physical, intellectual, and organizational -- which, together with the (dynamic) resource positions of their competitors, determine firms' current and future success.

**Description**

Wernerfelt (1984), building on Penrose (1959), proposed the strategic analysis of firms with a focus on resources instead of product markets. Wernerfelt introduced the term resource-position-barrier to denote resources which can provide sustained competitive advantage and described the attraction of resource positions as follows: "What a firm wants is to create a situation where its own resource position directly or indirectly makes it more difficult for others to catch up." This work was at the vanguard of a large research effort and the generation of new terminology, from "core-competence" (Prahalad and Hamel, 1990) to "core rigidity" (Leonard-Barton, 1992).

In addition to theoretical work, a large number of empirical studies by Rumelt (1991), Schmalansee (1985), Caves and Porter (1977), Clark and Fujimoto (1991), multiple IMVP efforts (summarized in Womack, Jones and Roos, 1990), and others have looked at firm versus industry performance for evidence of firm (resource) effects. Evidence of firm effects was found in many of these studies lending support to the resource-based view of firms.

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More recently, Peteraf (1993) summarized the resource literature and proposed a conceptual model in which the following four conditions must hold in order for firms to earn rents on their resources:

- Resources must be heterogeneous across firms.
- Resource must be imperfectly mobile.
- There must be ex-ante limits to competition for resources.
- There must be ex-post limits to competition for resources.

In this list, the first condition is held to be "sine-qua-non." Without heterogeneous resources, all firms have equal access to resources, so there can be no differentiation on a resource basis. Mobility is also important. If a firm controls resources that can be easily detached from the organization, then those resources will not provide the basis for sustained advantage. Ex-ante limits to competition for resources prevent the benefits accruing to these resources from being dissipated ahead of time in the competition for their acquisition. Ex-post limits to competition prevent benefits from being bid away after resource acquisition.

Barney (1991) also surveyed the resource literature and produced a set of requirements for resources to provide competitive advantage which overlaps those listed above by Peteraf.

- Resources must be valuable.
- Resources must be rare.
- Resources must be imperfectly imitable.

The value of a resource is determined in the market as a firm combines it with other resources to produce products. Resources that are very valuable but common are necessary to the firm. However, such resources do not
distinguish a company from its rivals. The last requirement, that resources be imperfectly imitable, is the most interesting. Barney lists three reasons why resources are hard to duplicate or substitute (emphasis in original article): (a) the ability to obtain the resource depends upon *unique historical conditions*; (b) the link between resource and competitive advantage is *causally ambiguous*; or (c) the resource is *socially complex*.

Unique historical conditions can arise from acquiring a resource, such as land, before anyone realizes its value. Causal ambiguity makes the importance of a resource to competitive success uncertain to everyone, including the entity that possesses the resource. Barney makes the point that if anyone knows the causal link between a resource and success in the market, that information will leak in the long run, and others will be able to acquire the resource and remove it as a differentiating factor. The last item Barney mentions, building socially complex resources, provides an area where companies are likely to attempt to achieve distinction through deliberate action. This is one way to make resources difficult to emulate that can be planned in advance.

Socially complex resources are difficult to replicate because they depend on a large number of actors and institutions. For example, Nippondenso developed the ability to manufacture a large variety of automobile parts, such as radiators and alternators, at nearly equal cost to one another (Whitney, 1993). This is important and interesting because product variety usually imposes a cost in product development and manufacturing. However, Nippondenso developed a manufacturing system that could make component parts at low cost. The company designed these components to be mixed and matched into a large variety of end products and developed an assembly system which could deal with all of the component combinations. Within the limits determined by component combinations, the Nippondenso system is extremely flexible. This capability requires the close integration of product design, component manufacturing, and product assembly systems.
These are all complex systems by themselves and making them work closely in tandem in a highly flexible, low cost, high quality way is a monumental achievement that other automobile parts manufacturers have yet to match. Nippondenso developed this manufacturing and design capability over a twenty-five year period by setting incremental targets for new capabilities to be added into the system.

Firm strategy from a resource point of view can be quite different than strategy driven by pure product market considerations. Collis and Montgomery (1995) note that the product market view of Porter's (1980) five structural forces failed to focus attention on what firms can do internally, instead focusing on their environment. Firms spent time assembling large portfolios of operations which appeared similar in product terms, but actually turned out to be difficult to merge at the operational level. Collis and Montgomery remark that the core-competence view is excessively inward-looking, but in combination with Porter's industry structure analysis, yields a resource-base view in which capabilities are judged valuable based on external criteria. These authors summarized much of the earlier work on resources into five tests for a resource to be competitively valuable:

- The test of inimitability: Is the resource hard to copy?
- The test of durability: How quickly does this resource depreciate?
- The test of appropriability: Who captures the value that the resource creates?
- The test substitutability: Can a unique resource be trumped by a different resource?
- The test of competitive superiority: Whose resource is really better?

Collis and Montgomery offer the most recent four-decade history of the Sharp corporation as a model of how to slowly move into new markets using existing technologies, and then to build new capabilities using existing
markets, creating a “virtuous circle” of growth in markets and capabilities. Figure 2.1 captures their description of the process graphically. Plus signs signify that a rise in one stock leads to a rise in the next stock in the loop. Negative signs signify that a rise in a stock leads to a fall in an associated stock.

Figure 2.1 - “Virtuous Circle” of Component Capability and Product Market Success

In the 1950s Sharp was a second rank assembler of consumer electronics. By backward integration into component technology, Sharp developed a capability that allowed it to move into many new markets. Success in the product markets generated sufficient financial resources to maintain and build component technology capabilities which in turn led to improved product market performance.
Currently, Sharp dominates the liquid crystal display market and is a major consumer electronics manufacturer. The story of Sharp raises the question of how to build valuable resources. This is primarily a question of organizational learning will be reviewed in a later section. First, consider how to measure resources.

**Measurement**

After reading lists of tests to determine whether a resource can provide sustained competitive advantage, there is still the question of exactly *what* a resource is, and how to measure one. Collis and Montgomery describe a range of resources from “highly fungible resources (such as cash, many kinds of machinery, and general management skills) to more specialized resources (such as expertise in narrow scientific disciplines).” In this sentence, the idea that some resources are more easily transferred to other settings than others is introduced. This quote also states that resources can be highly tangible and easily measured (cash), or more abstract concepts (management skills), which are much harder to quantify.

Henderson and Cockburn (1994) studied the pharmaceutical industry in an attempt to measure the effects of competence (firm-specific expertise in particular disciplinary areas, component competence) and information flow (cross firm-boundary information paths, cross disciplinary information paths) on pharmaceutical firm research productivity performance. Henderson and Cockburn offer compelling reasons to study program level data: “[T]he use of the research program allows us to be consistent across firms since it corresponds to the level of analysis at which firms organize their internal data.” They also note that funding is tied to projects, providing a reason why firms track expenses and outcomes at the project level. This is consistent with the author’s experience at GE Medical Systems, where new product development spending used to be funded in aggregate, but was changed to
correspond to programs that could be better assessed in terms of share and profit/unit once introduced to market.8

Henderson and Cockburn used interview data and internal company documents to develop their data set. They were unable to generate convincing measures of disciplinary competence and instead focused on integrative ability as measured by ties to the external scientific community (are publications rewarded) and program funding (top down versus committee). Calling integrative ability “architectural competence,” the authors found that companies that foster information exchange with outside scientists (publications) and internally (committee funding) have more productive research programs (measured by patent output).

In another study, Levinthal and Myatt (1994) investigated the back office operations of the mutual fund industry to find explanatory factors for the duration of relationships between mutual fund companies and suppliers of back-office services – with an emphasis on exploring mutual learning as a reason to continue business associations. Existing personal relationships, geography, and fraction of business already done with the supplier were strongly correlated with continuing relationships. When the mode of distribution (broker versus direct sales) changed, the likelihood of a supplier change went up dramatically. Levinthal and Myatt use this data set to assert that mutual funds and their back-office service suppliers develop co-specialized assets that are valuable until the nature of the relationship fundamentally changes. The continuing value of co-specialized assets in long-time business partners reduces the likelihood of separations as compared to firms that have done business for shorter periods of time. While not directly measuring of specialized assets, this study provides additional evidence that supports the view that business partners are

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8 Geoffrey Parker, GE Medical Systems 1986-1990.
reluctant to strand their specific investments, and so instead continue doing business with one another more often than firms that have less invested in one another.

Levinthal and Myatt generalize from their study to discuss the possibility of a "competency trap," where firms with high skills in one area may be reluctant to develop capabilities in other areas. This concern rests upon Cohen and Levinthal's (1990) concept of "absorptive capacity," which predicts that learning is easier when building upon an existing knowledge base. Extending this argument, the authors appear to be arguing that returns to learning effort are increasing in the amount of knowledge already accumulated. This is probably true, but only within a limited region. After a great deal of knowledge is accumulated about a subject, the amount of additional learning that is likely to accrue in that area should ultimately fall as diminishing returns set in. An S-curve of learning realization and cumulative learning effort, similar to Abernathy and Utterback's (1988) model for product and process innovation, seems a more appropriate model. The implication then becomes that firms must carefully time when to invest in new technologies, as returns to learning effort fall in existing technologies. Figure 2.2 attempts to capture this idea:

Figure 2.2 - Knowledge accumulation versus learning effort
The challenge of measuring resources remains a major issue in developing and testing resource-base theory, especially when looking for resources that confer competitive advantage. Based on earlier work discussed above, researchers should expect these competitively valuable resources to be difficult to measure due to social complexity and causal ambiguity. The measurement approach taken in this thesis (Chapter 5) is to directly ask individuals for their assessments of their own project-driven learning. A brief review of organizational learning is given to motivate some of the choices made in project-driven learning model developed in Chapters 3 and 4.

**LEARNING**

**Organizational Learning**

There is a large literature on organizational learning, and no attempt will be made here to cover it in a comprehensive manner. Instead surveys of the literature will be used to aid in understanding some of the basic issues; the types of learning, the actors involved, the constraints under which the actors operate, and the differences between individual learning and organizational learning.

Tsang (1997) makes the distinction between prescriptive research, which attempts to inform companies how to learn, and descriptive research, which observes how companies actually learn, and he suggests that the two streams of literature are not well integrated. In so doing, he collects some definitions that can be used here to help define what is meant by the term organizational learning. Tsang observes that “most definitions entail aspects of both cognitive and behavioral changes. The cognitive aspect is generally concerned with knowledge, understanding, and insights.” However, there is a split between definitions where some require a change of organizational
routine (Levitt and March, 1988). But, Tsang notes that there may be a long time lag between the acquisition and use of knowledge, and that existing knowledge is one component of complex decision-making processes. Hence, Tsang rejects a definition of organizational learning that includes behavioral change, and states that “the actual connection between learning and performance is an issue to be determined empirically instead of being assumed in the definition.” He cites Nicolini and Meznar (1995) who define organization learning “as a social construction which transforms acquired cognition into accountable abstract knowledge.”

From those covered by Tsang, the definition offered by Nicolini and Meznar is appealing in that it suggests a conversion of experience into a stock of knowledge, which may or may not be useful to the organization -- the stock’s usefulness depending upon the context in which it is accumulated. This stock of knowledge resides in individuals as well as a firm’s general operating procedures. Computer software and hardware offer a rough analogy: Routine procedures and “ways of doing things here” might be viewed as the software which helps give instructions to the actors, who are the individual members of the organization and form the hardware part of the analogy. Individual learning can be thought of as improvements to individual hardware elements. Organizational learning might be thought of as improvements to the overall operating system into which the individuals are integrated. For the hardware/software system performance to improve, there must be “hooks” between individual and organizational capabilities.

In another example, a firm might have capable workers, but it could be using dysfunctional management routines and hence achieve poor results. Contrast the 1987 performance of the NUMMI plant in Fremont, California, to the performance of a plant run similarly (Framingham, MA) under General Motors management (Womack, Jones, and Roos, 1990). The NUMMI plant, within one year of start-up, was achieving productivity and
quality levels many times better than other GM plants under more traditional (at the time) management systems. Interestingly, 80 percent of the NUMMI plant work-force worked at the same plant when GM ran it.

Miller (1996) recently synthesized much of the literature on learning methods and covered some of the same issues as Tsang, noting researchers who require a change in behavior as part of their definition of organizational learning (Cyert and March, 1963; March, 1989). Miller also rejects this requirement and states that "learning is to be distinguished from decision-making." Miller makes a distinction between voluntary and deterministic learning. By combining two types of learning with constraints on learning, he develops a framework along two axes, constraints and mode of thought/action, which is reproduced below:

**Miller's Taxonomy of Organizational Learning**

<table>
<thead>
<tr>
<th>Constraints (Voluntarism)</th>
<th>Methodological Thought/Action</th>
<th>Emergent Thought/Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Few constraints</td>
<td>Analytic</td>
<td>Synthetic</td>
</tr>
<tr>
<td>Action constrained</td>
<td>Experimental</td>
<td>Interactive</td>
</tr>
<tr>
<td>Action &amp; thought constrained</td>
<td>Structural</td>
<td>Institutional</td>
</tr>
</tbody>
</table>

In explaining this framework, Miller suggests that there is a correspondence between position in the organizational hierarchy and the constraints placed upon learning. At the upper levels, with few constraints, managers can undertake both deductive analytic exercises and more organic efforts to synthesize information. In the middle levels of organizations, learning is discussed as taking place within boundaries. For example, experiments represent attempts to incrementally increase knowledge around a locus. Interactive learning takes place in an environment of social and political activity and can be the result of conflicting objectives that must be resolved.
At the most constrained level, structural learning takes place in a preset information environment -- for example a monthly sales report might inform us that sales of an item are up 10 percent this month. Institutional learning is "determined by ideologies... laws, social norms, or personal values that shape managerial thinking. Here, learning is a product of indoctrination, either subtle or direct."

Miller suggests that high level analytic exercises are often under-informed by vital information that resides in lower levels of an organization, and can therefore be sterile. This supports Collis and Montgomery’s observation, noted above, that strategic planning efforts performed at the top of an organization hierarchy tended to ignore internal organizational issues in favor of looking outward.

In Miller's survey, systems thinking is described as one application of synthetic learning. Systems thinking allows people to view how organizations function together, and what the likely dynamics are in response to change. This type of thinking is described as very difficult -- and rigid, in the sense that once a system is described, it is very difficult to change any piece of it due to the repercussions for all other pieces of the system. Of course, this is a more realistic view than analysis that attempts to envision change to isolated pieces of a system only.

Here is a brief list of examples for some of the areas in which a business develops knowledge:

- knowledge about consumer preferences
- detailed mapping of consumer preferences to product attributes
- product attribute mapping to physical requirements (assumes a physical product)
- scientific knowledge of materials and processes
• internal organization dynamics
• market dynamics

Using Miller’s framework from above, these areas can be roughly categorized by mode of thought and action and by constraints. Knowledge of consumer preferences might be a fairly straightforward analysis based on surveys and focus groups, constrained by the desire to learn a specific set of preferences, such as those surrounding a type of stereo equipment. There should still be elements of methodical learning, as well as emergent learning in developing such consumer preference knowledge. Similarly, the effort to translate those preferences into product attributes will also have experimental and interactive elements, but would operate in a constrained environment; the product would be designed to meet a given set of requirements, not any conceivable demands a consumer might make of a device or service.

**Project-based organizational learning**

Organizational learning, as discussed by Miller, takes place both as a result of specific efforts and ongoing interactions within and between firms. The central concern in this thesis, learning that is generated by discrete projects, could take place in most of the categories listed by Miller. As part of project definition, relatively unconstrained analysis and synthesis can take place, the result of which would be the set of problem definitions the project is undertaken to solve. Once a project has begun, however, these problem definitions are unlikely to fundamentally change, and hence form a constraint around the types of learning that should be observed for the remainder of a project’s duration.

Acknowledging constraints on the learning environment of a project is potentially useful for predicting the direction of learning likely as an outcome of the project. Assuming that projects are begun after requirements are
determined, it can be assumed that most of the learning that occurs during a project is within set boundaries. For example, if a project is initiated to produce the next generation of microprocessor at Intel or Motorola, then there will be established targets for device performance along the metrics of calculations/second, data path size (in bits), and auxiliary functions embedded in the microprocessor, such as memory caches, arithmetic processing units, and video controllers. To achieve the desired speed metric, new device physics problems may require solution during the course of the project if the objective is to be met. This is likely to be an incremental effort, building heavily upon existing knowledge.⁹ Even if significant knowledge, unrelated to the project, is created during the course of a project, the memory system of the organization may not capture this knowledge for later use.

The issue of knowledge capture and transmission has been a problem at one automobile company that tries to transfer related learning from one product development project to another. Because the product development teams are quite autonomous, there is no incentive for engineers to share learning across projects; they usually have a number of other competing needs for their time.¹⁰ Given that the company has trouble capturing and transmitting relevant learning across project teams, it seems likely that learning which is unrelated to current product development efforts goes unrecorded unless there is an explicit effort to record that learning, including incentives to do so. The next section discusses incentives in the context of the principal-agent literature.

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⁹ At the limit of existing scientific knowledge, a major change, as described by Kuhn (1962), may be necessary to achieve performance improvements.
¹⁰ Geoffrey Parker, Chrysler Corporation, 1993.
INCENTIVES

There is a vast and growing literature dedicated to incentives and contracting. Hart and Holmstrom (1986), Holmstrom and Tirole (1989), and Holmstrom and Milgrom (1994) offer starting points to explore this work. The basic agency model describes the relationship between a principal who hires or contracts with an agent to perform some task. The theory is concerned with two problems. The first problem is that the goals of the principal and agent are usually different and in conflict. For example, the standard model has principal and agent each attempting to maximize their welfare, subject to a set of constraints (Holmstrom, 1979). The principal wishes to maximize the utility of revenue less the cost to generate that revenue -- including the agent's payment. The agent wishes to maximize the sum of the utility of his or her pay, and the dis-utility of the effort necessary to earn that pay. Compounding the problem of goal conflict is that observation of the agent's action by the principal can be costly.

One way to resolve the observability problem is to make the agent's compensation dependent upon the outcome. However, if the outcome is subject to uncertainty, then output is not a pure function of the agent's effort, and hence the agent faces some of this risk. This leads to the second problem, which is that the principal and the agent can have different attitudes toward risk. To the extent that the agent is risk averse, it becomes increasingly expensive for the principal to shift risk to the agent in order to induce desired behavior. The agent's compensation contract can be some combination of guaranteed pay (base salary) plus incentive pay (profit sharing). The agent's degree of risk aversion will determine his preference for fixed wages versus profit-sharing. The principal must take these preferences into account when designing a compensation contract.
Principal-agent models are often compared to the reference point of a cooperative outcome that maximizes total utility, and then show how this outcome cannot be reached due to agency problems described above. The goal is then to design a contract that brings total welfare closest to the "first-best" outcome. For example, if you assume a certain utility function, then shifting risk to the agent can be shown to mitigate the agency problem, raising overall utility. However, if too much risk is shifted to the agent, total utility begins to fall again. Firms that anticipate when agents will act in their own self-interest can design incentive systems to better align the goals of both parties.

In the next section, the human capital literature is introduced. Labor economics has drawn on the agency literature, but is generally concerned with the issue of wage growth and investment in learning as opposed to incentives for performance.

**Human Capital Theory**

The human capital branch of the labor economics field, beginning with Becker (1964) and Mincer (1974), offers a rich stream of literature that attempts to explain earnings profiles as a function of age, education, general training, and firm-specific training. This literature is relevant to this dissertation when one thinks of project execution as a form of training. Becker developed predictions about general and firm-specific training and the effects of this training on wages. In his model, Becker equated employees' marginal products to their wages and cost of training. For general training, a competitive labor market ensures that firms can not recover the cost of training, leading to the prediction that workers must pay for their own general training (usually by earning lower wages during the training period). The reason for this is that firms must offer employees a wage equal to the marginal product of their (general) labor. Otherwise, another firm could hire
them and still earn positive profit. For firm-specific training, Becker suggested that employees and firms should share the costs and benefits of specialized training. Sharing the benefits (paying more than a competitive wage) with employees helps to ensure that employees have incentives to stay and that employers can recoup their investments in specific training.

Mincer (1974) developed a model that explores the effect of schooling and work experience on wages. In Mincer's model, earnings grow quadratically. At job separations, Mincer's model predicts that an employee's wage should fall since the employee loses the product of his firm-specific capital. However, this result has not been seen in panel income data. Further work by Jovanovic (1979a, 1979b) offered a resolution to the conflict between observed data and Mincer's model. Jovanovic's model of search suggests that agents invest a fraction of their time searching for new jobs with a higher wage. As the current job improves, separations become less likely, which is associated with increased specific investment and longer job tenure. In one Jovanovic model, successive search yields a "good" job. Once agents are in a good job, they will invest less intensely in searching for a better job since the likelihood that they will find such a job goes down with the quality of the current job.

Acemoglu and Pischke (1998) offer a model of uncertain worker capability to explain why firms might pay for training in general human capital. In this model, firms learn of a worker's true capability slowly over time. This knowledge allows firms to capture some of the returns to general training that would otherwise be bid away in a full information market because competing firms do not know a worker's true marginal value. Instead, competitor firms assign a worker the expected value of the group to which the worker belongs.
Gibbons and Waldman (forthcoming), recently surveyed the human capital literature. They note the centrality to Becker's work of the hypothesis that firms and workers share the benefits of specific training. However, they note that Becker's analysis is limited by the implicit assumption that workers and firms can sign enforceable contracts specifying wages pre- and post-training and investment levels in firm-specific and general human capital. Their objection is similar to the issues raised by Williamson (1975, 1985) who developed a theory of asset specificity that predicts that both firms and individuals will under-invest in mutually specific assets due to an inability to commit before investment to share the benefits after investment. Gibbons and Waldman go on to review three decades of labor economics literature that has concentrated on issues of non-contractibility between individuals and firms as well as issues of information asymmetry (see Hashimoto, 1981; Hart and Moore, 1988; Ramey and Watson, 1997; Chang and Wang, 1996; Acemoglu and Pischke, 1998).

Chang and Wang's (1996) model merits additional comment because of the similarity, at first glance, to the models in this thesis. They develop a two-period model of employment where the worker has the option to leave the employment relationship after the first period. The focus of Chang and Wang's model is to determine the effect of information asymmetry on the firm's decision to invest in training the worker. The models developed in this thesis share some elements with Chang and Wang. There are two periods; the worker can leave after the first period; second period wages are determined by the productivity of the worker at an alternate employer. However, Chang and Wang focus on learning as a decision variable under the control of the firm, not the worker. Furthermore, they employ an exogenous overall minimum wage. Rational firms will set total wages equal to this minimum level. In general, Chang and Wang are answering a

\[ \text{11 Gibbons and Waldman cover human capital as part of a chapter in the Handbook of Labor} \]
different question than the one posed here. They ask “what is the effect on the firm’s training decisions of the un-observability of training levels to outside firms?” This thesis concentrates on asking “what is the effect on learning choices made by workers of the types of technology used by both the first-period employer and the (potentially different) second period-employer?”

In much of the agency and human capital literature, the focus is on effort incentives or the effect of information asymmetry. Most of the models in these literatures set the reservation wage to a constant. In this thesis, the reservation wage is endogenous -- the worker has the ability to make decisions which affect the reservation wage.

LITERATURE EXTENSIONS DEVELOPED IN THIS THESIS

The models in chapters 3 and 4 of this thesis retain Becker’s distinction between firm-specific and general capabilities and set an agent’s opportunity wage (or contract price) equal to the marginal product of general capability which an agent could receive in the outside market plus the marginal value of any firm-specific capability (at a competitor firm) an agent could accumulate within a single period. Also, following Becker, the firm has the option to share part of the difference between the agent’s marginal product and reservation wage. The most significant departure from the existing literature is the focus in this thesis on the different technologies firms employ and the effect of those technologies on the relationship between employer and employee or customer and supplier. In Becker, a worker’s reservation wage is a function of general capability gained prior to the current period:

Economics titled “Careers in Organizations: Theory and Evidence.”
\[ r = \sum_{i=1}^{t-1} \Delta g_i \]

\( \sum_{i=1}^{t-1} \Delta g_i \) represents all of the general capability acquired up to time \( t-1 \). Because the employee is fully rewarded (by a competitive labor market) for any increase in \( g \), Becker predicts that individuals must pay for their own general training.

In this dissertation, the opportunity wage is also a function of \( g \). However, the competitor firm's technology is also part of the reservation wage as follows:

\[ r = f\left( \sum_{i=1}^{t-1} \Delta g_i, \alpha_c, \beta_c \right) \]

The last two terms, \( \alpha_c \) and \( \beta_c \), represent the competitor firm's technology.

As noted above, a criticism of Becker has been the reliance on complete contracts and full information. In a departure from Becker, this thesis assumes that effort is non-contractible, so the choice of learning is left to the individual (or supplier). The current employer firm can affect the employee's willingness to invest in specific learning by paying more than the employee's reservation wage in a current period. If the firm is unable to commit to payments above reservation wages in the future, then current payments must be particularly large in order to induce an employee to make specific investments since there is no future payoff to the investment. Adopting output sharing from the standard agency model, the way the firm pays more than the reservation wage is to share a portion of the output which exceeds the employee's (supplier's) reservation wage. In this way, the firm can encourage investment in specific learning without having to directly specify
what the employee will learn. In fact, the firm does not need to observe the employee's choices. By observing output, competitor technology, and the firm's own technology, the firm can make choices about how much to share confident that the employee will make a profit-maximizing decision within the sharing framework set up by the firm.

Increasing the complexity of the reservation wage function makes it possible to explore more fully the differences (in terms of technology choices) between firms competing in the labor market and how those differences affect employee learning choices. The next two chapters develop in detail two models of learning as a function of firm sharing policies, firm technology, and competitor technologies. In Chapter 5, a project choice and learning data set is described and analyzed. The data set is used to test hypotheses derived from the models and to compare one model to the other.

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12 Employees and suppliers are assumed to be risk-neutral in this thesis.
3. CONSTRAINED PROJECT CHOICE AND LEARNING MODEL

The first model in this thesis attempts to provide guidance to the following question: How do firm policies (contracts) and firm technology (ability to productively use supplier capabilities) interact with the environment (a competitor's ability to use supplier capabilities) and the supplier's desired capability state to affect the supplier's choice of project? In this model, the supplier we are thinking of is an individual who has the capacity to work on only one project each period and whose learning is limited in each period. In the next chapter, we consider the supplier to be a firm that does not face the same capacity constraints as an individual.

This section develops a description of the project contract between a firm and a individual who are both cognizant of the capability development implications of the project they are about to undertake. This model contributes to the literature by making endogenous the individual's opportunity wage as a function of the individual's project choice, the firm's technology, and competitor technologies. This is new relative to a literature that has focused on eliciting optimal effort (Holmstrom, 1979) under varying scenarios of observability and contracting enforcement (Holmstrom and Milgrom, 1994) where opportunity wages are fixed and exogenous.

In the model presented below, the focus is on the influence competitor firm technologies have on the actions individuals take to improve their situation within an existing relationship. The model develops a simple case, that of a firm which contracts for the services of an individual over two periods. Capability is supplied by the individual in two varieties, firm-specific and general whose stocks in period t are denoted respectively as $f_i$ and $g_r$. There is assumed to be excess demand for the services of individuals. This means that the individuals always have the option to leave the existing relationship to
work at another firm. This is a model of contracting with "knowledge workers" such as engineers and software developers. The model offers guidance to firms on how their choice of technology investments will affect relationships with their knowledge-worker employees and how their choice of contracts will affect employee learning choices.

In the next chapter, the model is extended to supplier firms which can increase their capacity (at a cost).

GENERAL MODEL SETUP

Project driven learning
Building on Becker (1964), each project increases the individual's level of firm-specific and general capability in increments denoted by $\Delta f$ and $\Delta g$ respectively. The frontier of capability addition in the firm-specific axis ($\Delta f$) and the general axis ($\Delta g$) is assumed to lie on along a concave function, which is modeled (for mathematical tractability) as the upper right quadrant of the unit circle (see Figure 3.1). The frontier assumption captures the idea that individuals have limited capacity for learning in each period -- so that there is a trade-off between gains in firm-specific and general capabilities. The concave shape of the trade-off curve captures the idea of diminishing returns to learning effort in each period.14

13 This model is appropriate during a period, such as now, of excess demand for technically competent employees. The model implications are unlikely to hold when there are more workers than jobs and firms can bid employees against one another.
14 The diminishing returns to learning assumption is intuitively appealing: Additional insights become more difficult to obtain once the "low hanging fruit" has been collected. An alternate interpretation of the decreasing returns to learning assumption is that learning occurs along an S-shaped curve, where individuals always pass the inflection point and are in the diminishing returns portion of the curve.
Figure 3.1 - Project learning impact

\[ \Delta f \]

\[ \Delta g \]

In Figure 3.1 above, the set of projects, \{A,B,C,D,E\} is shown. These projects each have different capability impacts \( \Delta f \) and \( \Delta g \). Projects \{A,C\} are dominated in capability addition by the remaining projects \{B,D,E\} which lie on the frontier. Only those projects on the frontier will be considered for selection in any period. For modeling purposes, I assume a continuum of projects. Hence, \( \Delta f \) and \( \Delta g \) are modeled as continuous variables. The possibility that projects may have different financial (or other resource) costs, beyond opportunity cost, is not captured in the individual project choice model. We assume that individuals are constrained to one project in each period and that opportunity cost is the only cost the individual bears.

If capability in period 0 is assumed to be 0, then capability in periods 1 and 2 can be described in terms of \( \Delta f \) and \( \Delta g \).

\[
\begin{align*}
    f_0 &= 0, \quad g_0 = 0 \\
    f_1 &= \Delta f, \quad g_1 = \Delta g_1 \\
    f_2 &= \Delta f_1 + \Delta f_2, \quad g_2 = \Delta g_1 + \Delta g_2 \\
    \text{Where}\ 0 < \Delta f < 1, \ 0 < \Delta g < 1 \text{ in both periods.}
\end{align*}
\]
Production function

We refer to “the firm” as the holder of a technology that can make productive use of the individual’s firm-specific capability and general capability are, respectively, $\alpha$ and $\beta$. The firm’s technology, $\alpha$ and $\beta$, combines with the person’s capabilities, $f_i$ and $g$, to determine the firm’s incremental output (due to employing the individual) in each period.\textsuperscript{15} The focus is on the individual’s choices, so firm technology is held time invariant, while supplier capability is dynamic, yielding firm output:\textsuperscript{16}

$$y_i = \alpha f_i + \beta g,$$

Where $0 < \alpha < 1$, $0 < \beta < 1$

Making use of the constraint ($\Delta f^2 + \Delta g^2 = 1$) on learning in each period, the firm’s output equations for both periods can be expressed as a function of the individual’s choice of $\Delta f$ in each period.

$$y_1 = \alpha \Delta f_i + \beta \sqrt{1 - \Delta f_i^2}$$  \hspace{1cm} (3.1)  

$$y_2 = \alpha (\Delta f_i + \Delta f_2) + \beta (\sqrt{1 - \Delta f_i^2} + \sqrt{1 - \Delta f_2^2})$$  \hspace{1cm} (3.2)

Payments from firm to individual

The firm pays at least the individual’s opportunity wage plus a fraction of the firm’s output above that amount. If the firm’s output is lower than the individual’s opportunity wage, then no employment relationship is begun. The firm must decide how much of the surplus (incremental output - opportunity wage) to share with the individual. The firm can choose to share substantially, or pay the bare minimum necessary to secure the supplier’s cooperation. The implications of this choice are examined below.

\textsuperscript{15} The only firm output discuss here is incremental output attributable to the employment of the technology worker whose behavior we model.

\textsuperscript{16} A fuller treatment could include an interaction term between $f$ and $g$ as follows: $y_i = \alpha f_i + \beta g_i + \gamma f_i g_i$. The interaction term is left out of the model for analytic simplicity.
The mechanics of sharing are as follows: The individual has a reservation wage in each period that depends on an outside "competitor" (in the labor market) who can also employ the individual. If the firm's incremental output is greater than the individual's reservation price, then the sharing fraction determines how much of this difference will be given to the individual, and how much will be kept by the firm. In the first period, the individual's reservation is taken as fixed and exogenous. That is, the individual has already agreed to work for the firm, at which time the reservation payment was known to both parties.\(^\text{17}\)

Having agreed to work with the firm, the individual's first-period project choice is determined by the desire to maximize first-period plus second-period wages, which will be a function of the first-period reservation wage, second-period value to a (labor market) competitor firm, and the original firm's output in the first and second periods.

**Competitive environment**

The competitor's abilities to make productive use of the individual's firm-specific capability and general capability are, respectively, \(\alpha_c\) and \(\beta_c\).\(^\text{18}\) The competitor's technology can combine with the supplier's capabilities to determine output at the competitor as follows:

\[
y_c^* = \alpha_c f_i + \beta_c g_i
\]

If the individual were to join the competitor in the second period, the individual would strand any firm-specific capability built in the first period. Therefore, at the competitor, \(f_i = \Delta f_c\), and since general capability is

\(^{\text{17}}\)The first period reservation payment \(r_1\) is exogenous in this model. In an extension, it would be possible to generate \(r_1\) as the agent’s next best first period option in an economy with \(N\) firms. Solving for \(r_1\) would be non-trivial: The agent would search through the technologies of all firms for the best two-period option to calculate the next best first-period option.

\(^{\text{18}}\)The interaction between firm-specific and general capability could be captured as \(y_c\).
transferable, \( g_2 = \sqrt{1 - \Delta f_1^2} + \sqrt{1 - \Delta f_2^2} \). Again using the constraint on learning in each period, the competitor's second-period output can be expressed in terms of \( \Delta f_1 \) and \( \Delta f_2 \) as:\(^{19}\)

\[
y'_2 = \alpha_y (\Delta f_2) + \beta_y (\sqrt{1 - \Delta f_1^2} + \sqrt{1 - \Delta f_2^2})
\]

(3.3)

Assume that the competitor's maximum second-period output is less than the firm's maximum second-period output since the individual would be stranding firm-specific skills in the event the original relationship is severed. Thus the individual's second-period reservation payment is equal to the competitor's total output because the competitor would be willing to bid up to its entire incremental output to gain the services of the supplier.\(^{20}\)

**ANALYSIS OF LEARNING, OUTPUT, PAYMENTS, AND PROFIT**

With these basic elements in place, the impact of the firm's sharing choices and firm technology, as well as competitor technology on the individual's first-period project choices, firm output, payment to the individual, and firm profit, can be explored. In the two-period world under consideration, the individual's first-period choice of capability addition is the variable of primary interest. The effects of the individual's preparation for the second period will be seen on the learning investment (project choice) decisions made in the first period. In the second period, the individual optimizes his project choice given the decisions made in the first period.

In this section, two cases are analyzed:

---

\(^{19}\) If the individual leaves to work with the competitor in period 2, \( \Delta f_2 \) is specific to the competitor firm's technology.

\(^{20}\) Again, we are modeling the case where there is excess demand for the individual's skills. If the competitor fails to win the individual's services, there is no incremental output.
1. Central planning case Establishes first-best solution to maximize output
2. Sharing case Firm pays reservation wage and shares a fraction of the difference between the individual’s reservation wage and the firm’s output in both periods.

The central planning case is included to establish the first-best total output against which other equilibria are compared. In the sharing case, the firm cannot choose supplier projects. Instead, the firm chooses a sharing fraction $s$, the portion of the difference between the individual’s outside opportunity earnings and the firm’s incremental output.\(^{21}\) The degree of alignment between firm interests and individual interests depends upon the sharing fraction.

**Central Planning (First Best)**

To find the values for $\Delta f_1$ and $\Delta f_2$, which maximize output over both periods, solve directly for optimal project choice.

$$\max_{\Delta f_1, \Delta f_2} (y_1 + y_2)$$

Where $y_1$ and $y_2$ are defined in (3.1) and (3.2), the first-order-conditions for maximum output are:

$$\Delta f_1 \text{ (Central)} = \frac{\alpha}{\sqrt{\alpha^2 + \beta^2}}, \quad \Delta f_2 \text{ (Central)} = \frac{\alpha}{\sqrt{\alpha^2 + \beta^2}}$$

Conditions to establish the existence of an optimal solution are reported in Appendix A. The restrictions $0 < \alpha < 1$, $0 < \beta < 1$ ensure that the constraints $0 < \Delta f < 1$ (and $0 < \Delta g < 1$) are not violated.

---

\(^{21}\) This version of sharing is linear in output as opposed to sharing rules in the optimal incentives literature (reference goes here) which impose large penalties if an agent fails to take a specified action.
Under central planning, optimal learning varies with firm technology as expected. Using \( \partial_a \) to denote \( \frac{\partial}{\partial \alpha} \), observe that \( \partial_a \Delta f_i (\text{Central}) > 0 \). So desired firm-specific capability rises in the firm’s ability to make use of it. Since \( \partial_a \Delta f_i (\text{Central}) < 0 \), the optimal addition to firm-specific capability falls in the firm’s ability to make use of general capability.

**Sharing**

In general, first-best output is unachievable since the individual will make choices to maximize his or her payments. These choices will not usually lead to maximum incremental output or firm profit. The individual cares not only about maximizing output in the firm/supplier relationship, but also on the effect raising the opportunity payment has on total compensation. As it turns out, for a wide range of parameter values, it is in the firm’s interest to pay the individual a fraction of firm output in addition to their reservation wage. This issue will be explored in detail in the analysis below. First, here is an example to explain this particular choice of sharing arrangement.
Figure 3.2 - Output and payments over time for two technologies

Output, Payments

In the figure above, two output ($y_t$) curves, and two reservation wage ($r_t$) curves are shown for two technology and capability emphases, general and proprietary. In this example, the firm’s proprietary technology joined with an individual who has learned how to work with it creates more output than a general technology joined with an individual who has learned how to work with it. Conversely, when the individual invests in general capabilities, his reservation wages are higher than if he invests in more firm-specific capabilities. This means that the distance between output and reservation wages in the proprietary case is larger than the distance between output and reservation wages in the general case. If the firm chooses to share none of this distance, then a rational individual will act only to raise their own reservation wages, but not to improve output and would choose to invest only in general capabilities.

With this example in mind, an explicit model of individual project choice is developed.
Individual’s Problem

The individual’s reservation payments are \( r_i \) and \( y_i^c \) in the first and second period respectively. The firm’s incremental output due to the employment relationship is \( y_1 + y_2 \). If the firm agrees to meet the individual’s reservation wages and share fraction \( s \) of the difference between reservation wages and firm output in both periods, then payments to the supplier across both periods are \( r_i + s_1(y_i - r_i) + y_i^c + s_2(y_2 - y_i^c) \) which can be seen in the figure below.

**Figure 3.3 - Payments to employee as a function of \( s \)**

\[
\begin{align*}
\text{s=0} & & \text{s} & & \text{s=1} \\
& r_i + y_i^c & & r_i + s_1(y_i - r_i) + y_i^c + s_2(y_2 - y_i^c) & & y_i + y_2 \\
\text{Reservation Wage} & & \text{Firm Output} & & \\
\end{align*}
\]

The individual’s problem is to choose \( \Delta f_1 \) and \( \Delta f_2 \) to maximize the payment.

\[
\text{IP} \quad \max_{\Delta f_i} \left( (1 - s_1) r_i + \max_{\Delta f_2} ((1 - s_2) y_i^c) + s_1 y_i + \max_{\Delta f_2} (s_2 y_2) \right) 
\]

(3.4)

Solution of this problem proceeds backward from the second period. The individual must solve for the largest reservation wage and the largest firm output in the second period. The reason for separate maximizations in the second period is that the contract will pay at least the reservation wage, so the individual calculates what his maximum reservation wage is, even if he does not leave the employer firm.

Solving first-order-conditions to calculate the best \( \Delta f_2 \) to raise the second period reservation wage yields:
\[ \Delta_{f_2}^c \text{ (2nd period reservation payment maximizer)} = \frac{\alpha_c}{\sqrt{\alpha_c^2 - \beta_c^2}} \]

Given that the individual stays with the employer firm through the second period, the individual must also solve for the best second period output.

Solving first-order-conditions (taking positive roots) to calculate the best \( \Delta f_2 \) to raise payments from the firm yields:

\[ \Delta f_2 \text{ (2nd period firm output maximizer)} = \frac{\alpha}{\sqrt{\alpha^2 + \beta^2}} \]

The individual can now choose the best \( \Delta f_1 \) to maximize payments balancing reservation payments and firm payments through the sharing fraction \( s_i \).

\[ \Delta f_1^* = \frac{(s_i + s_c)\alpha}{\sqrt{(\alpha^2 + \beta^2)s_i^2 + 2s_i(\beta - \beta_c)\beta_c + \beta_c^2 + s_c^2(\alpha^2 + \beta^2 - 2\beta\beta_c) + 2s_i(\beta\beta_c + s_c(\alpha^2 + \beta^2 - \beta_c))}} \]

(3.5)

When \( s_i = s_c \), this simplifies to:

\[ \Delta f_1^* | (s_i = s_c) = \frac{2s\alpha}{\sqrt{4s^2\alpha^2 + 4s^2\beta^2 + 4s^2\beta\beta_c - 4s^2\beta\beta_c + \beta_c^2 - 2s\beta_c^2 + s^2\beta_c^2}} \]

(3.6)

Note that \( \alpha_c \) does not appear in the individual’s first-period choice. This is because the individual cannot make any first-period investments in the competitor’s proprietary technology. Also note that as the firm shares more output, the individual is more willing to invest in firm proprietary technology, that is:

\[ \partial_{s_i} \Delta f_1^* > 0, \partial_{s_c} \Delta f_1^* > 0 \]

(3.7)

In addition to the sensitivity of first-period capability choices to the firm’s choice of sharing fraction, the sensitivity of the supplier’s project choice to

\[ ^{22}\text{See Appendix A for proof.} \]
firm technology and competitor technology is of interest. The following relationships hold when the individual has project choice: 

\[ \partial_{\alpha} \Delta f_i^* > 0, \quad \partial_{\beta} \Delta f_i^* < 0 \]  

(3.8)

Individuals are willing to invest more in firm-specific capabilities as the firm's ability to make use of those capabilities rises. Conversely, the individual's willingness to make firm-specific capability investments falls in the firm's ability to use general capabilities.

**Firm's Problem**

Given the individual's choices, it would be desirable to solve for the firm's optimal sharing choice. The firm's problem is to maximize profit (incremental output - supplier payments) over \( s_i \):

\[ \text{FP} \quad \max_{s_1, s_2} \left( (1 - s_1)(y_1 - r_1) + (1 - s_2)(y_2 - y_2^c) \right) \]  

(3.9)

\[ \text{s.t.} \]

\[ \Delta f_1^* = -\frac{(s_1 + s_2)\alpha}{2(s_1(\beta - \beta_c)\beta_c + \beta_c^2 + \rho_s^2(\alpha^2 + \beta^2 - 2\beta\beta_c + \beta_c^2) + 2s_1(\beta\beta_c + s_2(\alpha^2 + \beta^2 - \beta\beta_c))} \]

\[ \Delta f_2 = \frac{\alpha}{\sqrt{\alpha^2 + \beta^2}} \]

\[ \left( (1 - s_1)(y_1 - r_1) + (1 - s_2)(y_2 - y_2^c) \right) \geq 0 \]

Substituting for the individual's choices generates a complex firm profit function which is not globally well behaved (see Appendix A), so analytic solutions for \( s_i^* \) are not reported. However, the function is well behaved within the defined constraints on the parameter variables. So, given sample parameter values, profit as a function of \( s_i \) is traced out in the graphs below.

---

23 See Appendix A for detail.
INDIVIDUAL MODEL EXAMPLES

Having solved for the individual's choices taking into account the firm's choice of sharing fraction, the firm's technology, and the competitor's technology, some of the model's implications can now be explored through a series of examples. In the first set of examples, restrict \( s \) to be the same over both periods. In the second set, the impact on firm profit of allowing \( s_2 \neq s_1 \) is explored.

Constrained model: sharing fractions \( s_2 = s_1 \)

Firm-specific learning and output

In the following graph, firm-specific knowledge accumulation in the first period is plotted for three cases: low competitor general technology \((\beta_c = 0.1)\), medium competitor technology \((\beta_c = 0.5)\), and high competitor general technology \((\beta_c = 0.9)\). The firm is assumed to have substantial proprietary technology and medium general technology \((\alpha = 0.9, \beta = 0.5)\). The first-best central planning solution is also plotted for comparison. In this example, assume \( s_2 = s_1 \).

Figure 3.4 \( \Delta f^*_1 \) versus \( s \), for multiple \( \beta_c \)

\[ a = 0.9, \beta = 0.5, s_2 = s_1 \]
In this graph, the effects of different competitor technologies can be seen on the individual’s willingness to invest in firm-specific technology. When the competitor’s ability to use general technology is low ($\beta_c = 0.1$ in this example), the sharing fraction must be very low before the individual makes a significant shift away from investing in the firm’s proprietary technology. However, when the competitor firm’s ability to use general technology is high ($\beta_c = 0.9$ here), the individual shifts learning investment away from the firm’s proprietary technology much more quickly as the sharing fraction $s$ falls. This makes sense. When $\beta_c$ is high and sharing is low, the individual can make general investments which will be of use in the next period. When the sharing level approaches one, the individual’s problem becomes the same as the central-planning output maximization problem, and the learning choices approach the first-best (for output) optimal solution.

The graph below shows total output versus sharing fraction for multiple competitor firm technologies.

*Figure 3.5- Output versus $s$ for multiple $\beta_c$*

$\alpha = 0.9, \beta = 0.5, s_y = s_t$

Again, when the competitor firm employs mostly proprietary technology ($\beta_c$ low), the individual does not quickly shift investment away from the original
firm's proprietary technology (hence lowering output) until sharing levels are very low. However, when the competitor employs general technologies ($\beta_c$ high), the individual invests in general technologies, distorting incremental output at the original firm further away from optimality as $s$ falls. Higher levels of competitor general technology give the individual more learning options and a greater opportunity to act in his self-interest, to the detriment of firm output.

**Payments to individual, profit for firm**

The next series of graphs explore the behavior of the supplier payment function and the firm profit function as technology and sharing parameters are varied.

*Figure 3.6 - Payments versus $s$ for multiple $\beta_c$*

![Graph showing payments versus s for multiple $\beta_c$.](image)

When the competitor employs little general technology, the individual's reservation payment level is lower, so total payments are lower than when the competitor firm employs substantial general technology.

The next graph plots firm profit against competitor general technology for different levels of competitor proprietary technology and sharing fraction.
Figure 3.7 - Firm profit versus $\beta_c$ for multiple $s_i$ (with $s_2 = s_1$)

This graph shows that, for these parameter values, low sharing ($s=0.1$) is more profitable than medium sharing ($s=0.5$) until the competitor firm's general technology is at a medium level ($b_c=0.55$). Medium sharing dominates both low and high sharing after this point. When the competitor's general technology parameter $b_c$ exceeds 0.85, high sharing is more profitable than low sharing.

In the next graph, the firm's incremental profit function is plotted against the sharing fraction, $s$, for a wide range of competitor general technology levels.\(^24\)

\(^{24}\) The graphs look substantially the same for different levels of competitor technology $\alpha_c$. 
The top curve represents firm profit when the competitor does not employ substantial general technology ($\beta_c = 0.1$). In this case, the profit-maximizing sharing parameter is 0.09. The bottom curve traces out firm profit over the range of possible sharing fractions when the competitor employs a high level of general technology ($\beta_c = 0.9$). In this case, the optimal sharing fraction is much higher at 0.43. For the scenarios above, varying the competitor's proprietary technology level $\alpha_c$ did not have a substantial impact on the results.

In the graph above, the firm's incremental profit function is concave over the valid range of the sharing parameter, $0 < s < 1$ (see Appendix A to view profit function over wider range of parameter values). This is not surprising since the firm's incremental profit function (3.9) is a trade-off between the firm's incremental output and the individual's reservation wage. The marginal benefits and marginal costs to the firm can be made equal through a choice of $s$. Increasing levels of $\beta_c$ lead to lower firm profit since the individual can raise his opportunity wage by investing in general capabilities. Higher levels of $\beta_c$ also lead to higher levels of optimal sharing as the firm attempts to entice the individual to invest in the firm's proprietary technology.
As seen below, when the firm is less invested in proprietary technology, the graph of firm incremental profit versus \( s \) has the same overall shape, but optimal sharing levels are lower.

*Figure 3.9 - profit versus \( s \) for multiple \( \beta_c \) - general technology emphasis*

\[
\begin{align*}
\alpha &= 0.5, \beta = 0.9, r_i = 0.4, \alpha_c = 0.5, s_2 = s_1
\end{align*}
\]

Determining the optimal sharing fraction for the firm analytically has proven intractable since the profit functions are not well behaved outside the limits \( 0 < s_i < 1 \) (see Appendix A). However, for selected parameter values, the optimal values can be calculated numerically. The graph below shows the optimal sharing fraction plotted against the competitor firm's general technology for three different firm technologies.

*Figure 3.10 - Optimal \( s \) versus \( \beta_c \)*

\[
\begin{align*}
\alpha_c &= 0.5, r_i = 0.4, s_2 = s_1
\end{align*}
\]
In the graph above, the firm's optimal sharing fraction increases in the competitor firm's general technology level for each of the three combinations of firm technology shown. When the firm employs substantial proprietary technology and medium general technology ($\alpha=0.9$, $\beta=0.5$), the optimal sharing fraction is higher than when the firm employs substantial levels of both firm-specific and general technologies. The firm's ability to use general capabilities balances against the firm's dependence on proprietary technology to lower $s$. The optimal sharing fraction is lowest among the scenarios shown when the firm employs medium proprietary technology and substantial general technology ($\alpha=0.5$, $\beta=0.9$). In this case, the firm has less proprietary technology to entice the individual to learn, so sharing is not as important as when the firm is heavily invested in unique technologies.

In the set of graphs below, firm profit is plotted against $s$, where $s$ can vary in each period.

**Constrained model: sharing fractions $s_2 < s_1$**

*Figure 3.11 - profit versus $s$ for two firm technologies*
In the figure above, four scenarios are plotted: $s_2$ is either the same as $s_1$, or is zero and the firm either emphasizes proprietary technology ($\alpha=0.9$, $\beta=0.5$) or general technology ($\alpha=0.5$, $\beta=0.9$). When the firm employs a general technology strategy, sharing levels in the first period are low whether or not the firm is constrained to share in the second period or is free to set $s_2=0$.

When the firm emphasizes proprietary technology, there is a large effect on the firm's choice of $s_1$ when $s_2=s_1$ or $s_2=0$. When $s_2=0$, it is in the firm's interest to set $s_1$ to a high level in the first period ($s_1^*=0.65$) in order to encourage the individual to make substantial investment in the firm's proprietary technology for which there will be no payoff in the second period ($s_2=0$). However, when the firm can set $s_2=s_1$, then the firm need not share so much in the first period ($s_2=s_1^*=0.33$) since the individual is more willing to make firm-specific investments for which there will be a payoff in the second period.

In the figures below, firm profit is plotted against the entire range of possible values of $s_1$ and $s_2$ for different combinations of firm technology and competitor technology.

Figure 3.12 - profit versus $s_1$, $s_2$ firm generalizes, competitor specializes
In this example, the firm employs a general technology ($\alpha=0.5$, $\beta=0.9$), while the competitor employs a more proprietary technology ($\alpha_c=0.9$, $\beta_c=0.5$). In this example, the firm's optimal choice of $[s_1, s_2]$ is $[0, 0.205]$ which yields profit of 0.955. If the second period sharing fraction is constrained to be the same as the first period, then the optimal $s$ would be 0.08 in both periods. Profit in the $s_2=s_1$ case would be 0.938. The firm benefits from the ability to make a credible promise to share in the second period. If sharing in the second period were zero, the optimal choice of $s_1$ would be 0.12 and overall profit would be 0.927.

In the next example, both the firm and the competitor employ specialized technologies.

Figure 3.13 - profit versus $s_1$, $s_2$, firm and competitor both specialize

In this example, the firm's optimal choice of $[s_1, s_2]$ is $[0, 0.52]$ yielding profit of 0.88. The large sharing fraction in period two is the result of the firm's need to encourage the individual to invest in proprietary technology. When the sharing level is constrained to be the same across both periods, then the firm's optimal choice of $s$ would be 0.28 and profit would be 0.80. If the firm cannot make a credible promise to share then $s_1=0$. In this case the firm's best choice of $s_1$ would be 0.56. Profit is lowest at 0.71 when the firm cannot commit to share in the second period.
The last example shows the consequences of the firm's sharing choices when the competitor employs general technologies while the firm employs more proprietary technology.

**Figure 3.14 - profit versus s₁, s₂ firm specializes , competitor generalizes**

In the figure above, the firm's optimal choice of \( \{s₁, s₂\} \) is \( \{0, 0.76\} \) yielding profit of 0.71. Again, the large sharing fraction in period two is the result of the firm's need to encourage the individual to invest in proprietary technology. Here, the competitor offers a strong alternate use for general capabilities the individual might develop, so the firm must share substantially in the second period. If sharing is constrained such that \( s₁ = s₂ \) then the firm's optimal choice of \( s \) is 0.43 yielding a profit of 0.47. If the firm cannot make a credible promise to share such that \( s₂ = 0 \), then the firm's best choice of \( s₁ \) would be 0.72. Profit is lowest in the no-commit case at 0.18.

**DISCUSSION OF INDIVIDUAL MODEL**

Consider two firms. The first firm is a new start-up in Silicon Valley which is attempting to develop and market a novel computer technology. In the tradition of Silicon Valley, each of the employees at this firm is given stock...
options. The second firm is a large established company where options and other forms of stock market driven compensation are not offered to employees until they reach senior levels of management. For the start-up firm to be successful, employees must invest in proprietary technology which is of no current use to any other firm. Conversely, the established firm makes use of technologies which are widely used. For our purposes, think of the start-up firm as a high-sharing company and the larger firm as a low-sharing company (we constrain $s_2=s_1$ for simplicity).

Figure 3.15 - Example of two firm sharing/technology strategies

Assume that there is only one large firm in this industry. The start-up firm sees the large firm as its competition for employees (other start-up firms don't appeal to employees at the first start-up since they also work with proprietary technologies). Since this large firm employs a number of widely used technologies, the $\beta_c$ seen by the small firm is quite high. Therefore the start-up finds it more profitable to share output in order to prevent employees from developing general capabilities instead of investing in the firm's new technology. The established firm sees the start-up firms as its competition for employees. Since each start-up firm is employing mostly new, specialized technology, the $\beta_c$ seen by the established firm is low, and so the firm finds it profitable to offer minimal sharing.
With a model built up from fairly simple elements, explanations can be offered for the complex choices made by firms and individuals as a function of the competitive environment, the firm's technology choices, and the firm's contract offers. In the next chapter, the model is modified to capture some of the features of the supplier as a firm.
4. UNCONSTRAINED PROJECT CHOICE AND LEARNING MODEL

This chapter analyzes a model of supplier firm project choice. In the previous model of an individual’s project choice and learning, the total amount the individual could learn was constrained and the combination of firm-specific and general learning was assumed to trace out a concave function (taken as the unit circle for analytic simplicity). When considering supplier firms, we allow for unlimited learning in each period, but impose an increasing cost assumption for each increment of learning. The earlier model of individual learning did not include a cost since individuals were assumed to be able to choose only one project, at equal cost, in each period.

SUPPLIER FIRM LEARNING MODEL SETUP

Supplier firm learning and costs

If capability in period 0 is assumed to be 0, then capability in periods 1 and 2 can be described in terms of Δf and Δg.

\[ f_0 = 0, \quad g_0 = 0 \]
\[ f_1 = Δf_1, \quad g_1 = Δg_1 \]
\[ f_2 = Δf_1 + Δf_2, \quad g_2 = Δg_1 + Δg_2 \]

The cost \( c \) for learning Δf and Δg in each period is assumed to be convex s.t.:

\[ \lim_{Δf→0} \frac{∂c(Δf)}{∂Δf} = 0, \quad \lim_{Δf→∞} \frac{∂c(Δf)}{∂Δf} = ∞ \]
\[ \lim_{Δg→0} \frac{∂c(Δg)}{∂Δg} = 0, \quad \lim_{Δg→∞} \frac{∂c(Δg)}{∂Δg} = ∞ \]

For analytic simplicity, assume that costs in each period are quadratic in the amount of learning, i.e.:
\[
c(\Delta f) = \frac{1}{2} k_f \Delta f^2, \quad c(\Delta g) = \frac{1}{2} k_g \Delta g^2
\]  
(4.1)

\(k_f\) and \(k_g\) are constants to differentiate the costs of general and firm-specific learning.\(^{25}\)

**Production function**

As in the individual choice model, the firm's abilities to make productive use of the supplier's firm-specific capability and general capability are, respectively, \(\alpha\) and \(\beta\). The firm's technology, \(\alpha\) and \(\beta\), combines with the supplier's capabilities, \(f_i\) and \(g_i\), to determine incremental output in each period. Because the focus is on supplier choices, firm technology is held time invariant, while supplier capability is dynamic, yielding incremental output:\(^{26,27}\)

\[
u_i = \alpha f_i + \beta g_i
\]

Where \(0 < \alpha < 1, 0 < \beta < 1\)

The firm's output equations for each period in the model can be expressed as a function of the supplier's choice of \(\Delta f\) and \(\Delta g\).

\[
u_1 = \alpha (\Delta f_1) + \beta (\Delta g_1)
\]

\[
u_2 = \alpha (\Delta f_2 + \Delta f_3) + \beta (\Delta g_1 + \Delta g_2)
\]

(4.2)

(4.3)

Again, the firm pays the supplier at least its opportunity payment plus a fraction of incremental output from the relationship. The implications of

---

\(^{25}\) Investigating a more complex learning cost function of the form \(k_f \Delta f^2 + kk_f g + k_g \Delta g^2\) is interesting for future work. Another variation would be to make learning costs in the second period dependent on the volume of learning done in the first period. These variations are outside the scope of the current investigation.

\(^{26}\) Output in the unconstrained supplier firm project choice model is denoted as \(u\) to distinguish it from the previous individual model of constrained project choice.

\(^{27}\) A fuller treatment could include an interaction term between \(f\) and \(g\) as follows:

\[u_i = \alpha f_i + \beta g_i + \gamma f g_i\]

The interaction term is left out of the model for analytic simplicity.
how much of the surplus (incremental output-opportunity payment) the firm shares are examined below.

**Competitive environment**

The competitor's abilities to make productive use of the supplier's firm-specific capability and general capability are, respectively, $\alpha_c$ and $\beta_c$. The competitor's technology can combine with the supplier's capabilities to determine output as follows:

$$u_c^i = \alpha_c f_i + \beta_c g_i$$

In the two-period world under consideration, the competitor firm can only work with the supplier in the second period. The supplier would strand any firm-specific capability at the first firm if it were to work with the competitor in the second period. Therefore, competitor output in period two would be:

$$u_c^2 = \alpha_c (\Delta f_2) + \beta_c (\Delta g_1 + \Delta g_2)$$

(4.4)

Assume that the original firm's incremental output is greater than the first-period reservation payment plus the competitor's incremental output in the second period. This assumption makes the supplier's second-period reservation payment equal to the competitor's output in period two. The firm's problem includes a constraint that profit be greater than zero to ensure this assumption is met.
Supplier problem

The supplier’s reservation payments are \( r_1 \) and \( u_2^c \) in the first and second period respectively. The firm meets the supplier’s reservation payments as a condition of doing business. The firm also has the option to share some portion \( s \) of the difference between incremental output and reservation payments. In this version of the model, the supplier faces costs to learning which must be included in its decision problem. The supplier’s gain over two periods is: (reservation payment + \( s \) (incremental output - reservation payment) - supplier learning costs). Substituting and simplifying, the supplier’s gain is:

\[
(1 - s_1) r_1 + (1 - s_2) y u_2^c + s_1 u_1 + s_2 u_2 - c(\Delta f_1) - c(\Delta f_2) - c(\Delta g_1) - c(\Delta g_2)
\]

(4.5)

The supplier’s problem is to choose learning levels in the first and second periods that maximize this gain.

\[
\max_{u_1, \Delta g_1} \left( (1 - s_1) r_1 + s_1 u_1 - c(\Delta f_1) - c(\Delta g_1) + (1 - s_2) \max_{u_2, \Delta g_2} \left( u_2^c - c(\Delta f_2) - c(\Delta g_2) \right) + s_2 \max_{u_2, \Delta g_2} \left( u_2 - c(\Delta f_2) - c(\Delta g_2) \right) \right)
\]

This problem is solved in two stages. In the second period, the supplier’s reservation payment is determined by the incremental output a competitor firm would create through employing the supplier’s services. The reservation payment is the maximum value of the competitor’s second-period output, \( u_2^c \). The second-period problem is:

\[
(1 - s_2) \max_{u_2, \Delta g_2} \left( u_2^c - c(\Delta f_2) - c(\Delta g_2) \right) + s_2 \max_{u_2, \Delta g_2} \left( u_2 - c(\Delta f_2) - c(\Delta g_2) \right)
\]

The second-period learning choices that maximize the reservation payment piece of this problem are:
\[ \Delta f_2 = \frac{\alpha}{k_f}, \Delta g_2 = \frac{\beta}{k_g} \]

The second-period learning choices that maximize the original firm’s output piece of the problem are:

\[ \Delta f_2 = \frac{\alpha}{k_f}, \Delta g_2 = \frac{\beta}{k_g} \]

The supplier can now choose first-period learning levels knowing its best second period choices, balancing the benefits of raising the reservation payments or raising firm output. After substitution for second period choices and the cost function, the supplier’s first-period problem is:

\[
\max_{\Delta f, \Delta g} \left[ (1-s_i) \left( r_i - \frac{k_i \Delta f_i^2}{2} - \frac{k_g \Delta g_i^2}{2} \right) + s_i \left( \alpha \Delta f_i + \beta \Delta g_i - \frac{k_i \Delta f_i^2}{2} - \frac{k_g \Delta g_i^2}{2} \right) \right] \\
= s_i \left( k_f \alpha + k_f \beta + k_g \beta - \frac{k_g \Delta g_i}{2} \right) + (1-s_i) \left( k_f \alpha + k_g \beta - \frac{k_g \Delta g_i}{2} \right)
\]

The first-order conditions for this problem are:

\[ \Delta f_i^* = \frac{(s_i + s_2) \alpha}{k_f}, \Delta g_i^* = \frac{(s_i + s_2) \beta + (1-s_i) \beta}{k_g} \]  

**Firm problem**

Given the supplier’s best response choices, we can examine the firm’s decision problem. The firm chooses \( s \) to maximize profit (incremental output - supplier payments). After simplification, this problem is:

\[
\text{FP} \quad \max_{s_i, r_i} \left[ (1-s_i)(u_i - r_i) + (1-s_2)(u_2) \right]
\]

Subject to the firm’s participation constraint and supplier choices:
\[
\max_s \left( (1-s_1) \left( u_1 - r_1 \right) + (1-s_2) \left( u_2 - u_2^* \right) \right) \geq 0
\]

\[
\Delta f_1^* = \frac{(s_i + s_s)\alpha}{k_f}, \quad \Delta g_1^* = \frac{(s_i + s_s)\beta + (1-s_s)\beta_c}{k_s}
\]

\[
\Delta f_2 = \frac{\alpha}{k_f}, \quad \Delta g_2 = \frac{\beta}{k_s}
\]

Substituting for the supplier's choice, the firm's profit function over both periods is:

\[
\pi_i + \pi_s = \frac{1}{k_f k_s} \left( \begin{array}{c}
\alpha^2 k_s - \alpha^2 k_s (s_i + s_s - 2)(s_i + s_s) + k_f k_s (\alpha^2 (s_i - 1) - \alpha^2 s_s) \\
+k_f \left( \beta^2 + k_f (s_i - 1) - (\beta (s_i + s_s - 2) - \beta_s (s_i - 1))(\beta (s_i + s_s) - \beta_s (s_i - 1)) \right)
\end{array} \right)
\]

The first-order condition on \(s_i\) for this function is:

\[
s_i^* = \frac{2\alpha^2 k_s (1-s_s) + k_f (k_f r_1 + 2\beta(1-s_s)(\beta - \beta_s))}{2(\beta^2 k_f + \alpha^2 k_s)} \tag{4.8}
\]

\[
s_s^* = \frac{2\alpha^2 k_s (1-s_s) + k_f (k_f r_1 + 2(-\beta + \beta_s + \beta_s^2))}{2(\alpha^2 k_s + k_f (\beta - \beta_s)^2)} \tag{4.9}
\]

When \(s_i\) and \(s_s\) are constrained to be equal, the first-order condition is:

\[
s^* = -\frac{4\alpha^2 k_s + k_f (4\beta^2 + k_f (\beta - \beta_s) + 2\beta (\beta_s + \beta_s) - \beta_s (\beta - \beta_s) (2+k_s^2))}{2(4\alpha^2 k_s + k_f (\beta - \beta_s)^2)} \tag{4.10}
\]

The behavior of the \(s_i^*\) functions is dependent upon the parameter values, so comparative statics are not reported. In the next section, multiple graphical examples are explored. First, \(s_i\) and \(s_s\) are constrained to be the same. Then, the effect on firm profit of relaxing this constraint is explored.
The relationship between \( \alpha \) and \( \alpha_c \) as well as \( \beta \) and \( \beta_c \) has a substantial impact on the whether the \( s_i \) functions increase or decrease in various parameters.

**GRAPHICAL EXAMPLES**

The behavior and some of the implications of the supplier firm project choice model are explored through a series of examples.

**Graphical Examples:** \( s=s_2=s_1 \)

**Supplier gain and firm profit**

In the figure below, the supplier's gain is plotted against the sharing fraction for three different levels of a competitor's ability to use general capabilities (\( \beta_c \)).

**Figure 4.1 - Supplier gain vs. \( s \)**

\[
\begin{array}{c}
\text{Supplier Firm Gain, per 1 and 2} \\
\end{array}
\]

\[
\begin{array}{c}
\alpha = 0.9, \beta = 0.5, \alpha_c = 0.5, r_1 = 0.4, k_1 = 1, k_2 = 1.
\end{array}
\]

The supplier's gain includes both payments from the firm and the costs to learning in each period. The supplier's gain increases in \( \beta_c \) since the supplier's reservation payments increase in \( \beta_c \). As the sharing fraction
approaches one, the reservation payment becomes irrelevant and the supplier's gain approaches the same value for all competitor technologies.

The figure below traces out the firm's profit (output-payments) as a function of $\beta_c$ for three sharing levels.

**Figure 4.2 - Firm profit vs. $\beta_c$**

In the figure above, a medium sharing level ($s=0.5$) dominates low ($s=0.1$) and high ($s=0.9$) sharing levels for the firm and competitor technologies shown.

Recall that firm profit = output-((1-s)* reservation payments + s(output)).
This generates the convexity in s seen in the example above. In the next figure, firm profit is shown as a function of sharing levels for three different competitor technologies {$(\alpha_c=0.5, \beta_c=0.1)$, $(\alpha_c=0.5, \beta_c=0.5)$, $(\alpha_c=0.5, \beta_c=0.9)$}. 
Figure 4.3 - Firm profit vs. $s$, specialized firm technology

$\pi_1 + \pi_2$

$\alpha = 0.9, \beta = 0.5, \alpha_c = 0.5, r_1 = 0.4, k_1 = 1, k_2 = 1$

The example above is for a firm that employs specialized technologies ($\alpha = 0.9$, $\beta = 0.5$). For the parameters shown, the optimal $s$ is an increasing function of $\beta_c$.

In the next example, given a firm with a more general technology emphasis ($\alpha = 0.5, \beta = 0.9$), the optimal sharing level is highest when the competitor employs minimal general technology ($\beta_c = 0.1$).

Figure 4.4 - Firm profit vs. $s$, generalist firm technology

$\pi_1 + \pi_2$

$\alpha = 0.5, \beta = 0.9, \alpha_c = 0.5, r_1 = 0.4, k_1 = 1, k_2 = 1$
In the figure above, the optimal s is shown not to increase monotonically in $\beta_c$. The figure below plots the optimal path for s as a function of $\beta_c$ for multiple firm and competitor technologies.

**Figure 4.5 - Optimal s vs. $\beta_c$, multiple firm technologies**

![Graph showing the optimal s vs. $\beta_c$ for different values of $\alpha$ and $\beta$.](image)

$a=0.5, r=0.4, k=1, k^*=1$

In the figure, the highest sharing levels occur when the firm's technology levels are lowest at $\alpha=0.5, \beta=0.5$. The optimal s function traces out a series of convex curves in which the slopes at any level of competitor general technology are determined by the fixed parameter values. The convexity arises from the need to motivate the supplier to work at all when $\beta_c$ is low and the need to encourage the supplier to invest in proprietary technology when $\beta_c$ is high.

In the following series of graphs, $s_1$ and $s_2$ are allowed to vary independently from one another.
Graphical Examples: \( s_2, s_1 \) vary independently

**Figure 4.6 - \( \pi_1 + \pi_2 \) versus \( s_1, s_2 \) (firm generalizes, competitor specializes)**

\[ r_1 = .4, \ a_c = .9, \ \beta_c = .5, \ a = .5, \ \beta = .9, \ k_f = k_g = 1 \]

In the graph above, total firm profit over both periods is plotted against all possible values for \( s_1, s_2 \). When the firm is constrained to offer the same sharing fraction over both periods, the common fraction is set at 0.45, resulting in profit of 0.80. In the case where the firm cannot promise to share in the second period, \( s_2 = 0 \), the firm sets \( s_1 = 0.76 \), resulting in profits of 0.87. When the firm can offer a binding promise and is free to set any sharing rule, the firm still sets \( s_2 = 0 \) and \( s_1 = 0.76 \), resulting in profits of 0.87. These results are summarized in the table below.

<table>
<thead>
<tr>
<th></th>
<th>( s_2 = s_1 )</th>
<th>( s_2 = 0 )</th>
<th>( s_1, s_2 ) independent</th>
</tr>
</thead>
<tbody>
<tr>
<td>( s_1 )</td>
<td>0.45</td>
<td>0.76</td>
<td>0.76</td>
</tr>
<tr>
<td>( s_2 )</td>
<td>0.45</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>profit</td>
<td>0.80</td>
<td>0.87</td>
<td>0.87</td>
</tr>
</tbody>
</table>

In the next example, we assume that both the firm and the competitor pursue specialized technologies.
Figure 4.7 - p1+p2 versus s1, s2 (firm specializes, competitor specializes)

\[ r_1 = 0.4, \alpha_x = 0.9, \beta_x = 0.5, \alpha_2 = 0.9, \beta_2 = 0.5, k_1 = k_2 = 1 \]

The table below details optimal choices of \( s_i \) under three cases (\( s_2 = s_1, s_1 = 0, s_1, s_2 \) independent).

<table>
<thead>
<tr>
<th></th>
<th>( s_2 = s_1 )</th>
<th>( s_2 = 0 )</th>
<th>( s_1, s_2 ) independent</th>
</tr>
</thead>
<tbody>
<tr>
<td>( s_1 )</td>
<td>0.52</td>
<td>0.95</td>
<td>0.80</td>
</tr>
<tr>
<td>( s_2 )</td>
<td>0.52</td>
<td>0</td>
<td>0.20</td>
</tr>
<tr>
<td>profit</td>
<td>0.80</td>
<td>0.81</td>
<td>0.82</td>
</tr>
</tbody>
</table>

In this example with the firm and competitor both pursuing specialized technologies, the firm’s optimal choice of \( s \) has minimal impact on overall profit. This is because the supplier has little recourse since the competitor does not highly value general capabilities.

The example below is of particular interest. Here, the competitor uses substantial general technology (\( \alpha_x = 0.5, \beta_x = 0.9 \)), while the firm uses more specialized technology (\( \alpha = 0.9, \beta = 0.5 \)).
Figure 4.8 - $\pi_1 + \pi_2$ versus $s_1, s_2$ (firm specializes, competitor generalizes)

$r_1 = .4, \alpha_c = .5, \beta_c = .9, \alpha = .9, \beta = .5, k_t = k_g = 1$

The firm's optimal choices under three scenarios, and the impact on profit are shown below.

<table>
<thead>
<tr>
<th></th>
<th>$s_2 = s_1$</th>
<th>$s_2 = 0$</th>
<th>$s_1, s_2$ independent</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s_1^*$</td>
<td>0.55</td>
<td>0.76</td>
<td>0.30</td>
</tr>
<tr>
<td>$s_2^*$</td>
<td>0.55</td>
<td>0</td>
<td>0.81</td>
</tr>
<tr>
<td>profit</td>
<td>0.66</td>
<td>0.31</td>
<td>0.72</td>
</tr>
</tbody>
</table>

Profit in the $s_2 = s_1$ scenario is 0.66 while profit in the $s_2 = 0$ scenario is 0.31. When there is a substantial outside market for general capabilities ($\beta_c = 0.9$) and the firm uses substantial proprietary technology ($\alpha = 0.9$), the inability to commit to share has a large negative impact on firm profitability. Contrast this to the situation in the first two examples (firm generalist/competitor specialist, firm specialist/competitor specialist). In these examples, the inability of the firm to commit to $s_2 > 0$ had a minimal impact on profitability and was optimal in one case. Maximum profit is reached in each of the examples when the firm can set $s_1$ and $s_2$ independently.
In the section below, the model is applied to an automotive industry example. The decisions made by two firms (who compete in the market for supplier services) are shown as a function of their technologies.

Discussion of model analysis and automotive industry example
In 1993 Jose Ignacio Lopez de Arriortua developed a purchasing program at GM whereby suppliers compete in global competition with one another in an attempt to force suppliers to bid at the lowest possible amount they would take for the business.\(^{28}\) Though GM said it was improving supplier relationships in 1995, there were problems with an engine manifold directly traced to supplier under-investment in 1996. And in 1997, there was a wide perception among suppliers that GM was still the most "cut-throat" automobile assembler in the United States with which to do business.\(^{29}\)

Contrast the suppliers' view of GM with that of Chrysler. Dyer (1996) argues that Chrysler has assembled an "American Keiretsu" through the adoption of a highly cooperative set of supplier relationships. Chrysler adopted a sharing policy with its suppliers (the SCORE program) when it changed its supplier relationships as part of a major re-organization around 1990. As part of this program, suppliers can retain half of any savings from productivity improvements that exceed those in the original agreement.\(^{30}\)

Let GM be categorized as a low-sharing company, and Chrysler as a high-sharing company. Though suppliers have been diversifying their customer

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\(^{28}\) Chicago Tribune, Transportation Section, Pg. 7, September 5, 1993.

\(^{29}\) See: "Inside GM's global purchasing; it's a tough process, but they're working toward warmer supplier relations; General Motors Corp.; part 1," *Ward's Auto World*, Vol. 31; No. 4; Pg. 45, April, 1995;

"Manifold Shortage Reveals Cost of Squeezing Supplier," *Automotive News*, Pg. 3, Jan 22, 1996;


base as Japanese and European transplants have set up operations in the United States, in Detroit most suppliers still do the majority of their business with GM, Chrysler and Ford. For this discussion, ignore Ford and assume that a desired supplier works only with GM or Chrysler. These firms then provide the $\beta$, for one another. Furthermore, Chrysler's $\beta$ ($\beta_c$ to GM) should be fairly low while GM's $\beta$ ($\beta_g$ to Chrysler) should be quite high. Chrysler's low $\beta_c$ comes about as part of its re-organization to platform-based product development. Chrysler reduced its internal engineering capability and began to rely much more heavily on its supplier base for new product development and engineering. Therefore, Chrysler has a relatively low general capability to use suppliers, since it depends upon suppliers to work with the company on an on-going basis and to provide Chrysler-specific information transfer from one project to another.\textsuperscript{31} In contrast, GM has retained substantially more internal capability than Chrysler. In part, they have had to do this since a result of their purchasing policy is that they must be able to continue operations after switching suppliers.

One of the graphs from the examples above helps to interpret this example of firm-supplier behavior from the automotive industry. In the figure below, the optimal $s$ (when $s = s_2 = s_1$) is plotted against $\beta_c$ for two technologies. Interpret the generalist technology strategy as GM's and the specialist technology strategy as Chrysler's. The bullets denote each firm's response to the other if there were only two firms contracting for supplier capabilities.

\footnote{Field interviews, Geoffrey Parker, Summer, 1993.}
GM finds it profitable to maintain a lower sharing fraction than Chrysler in part because other automobile assemblers pursue longer term relationships with suppliers and build up proprietary technologies with those suppliers. Consequently, those other assemblers have a lesser ability to switch suppliers easily - so GM faces competitor firms with a lower $\beta_c$. Conversely, Chrysler finds it more profitable to maintain a higher sharing fraction in part because GM represents a high $\beta_c$ competitor to whom suppliers can turn if they are not satisfied with the Chrysler/Supplier relationship.

As in Chapter 3, using a simple model with a minimal number of parameters, an explanation for firm sharing behavior as a function of firm and competitor technologies can be given. The next chapter presents and analyzes a data set designed to systematically explore project choice using survey data.
5. PROJECT CHOICE EMPIRICAL EVIDENCE

A data set to explore project choice among technology professionals has been collected from eight firms in the software, electronics, consulting, and space hardware industries. Scientists, engineers, and programmers at these firms were asked to evaluate how much they learn from their projects and whether that learning is generally applicable or specific to the firm in which they are employed. They were also asked a series of questions about project performance, incentives, motivation, industry experience, and personal background. Relationships between these variable are explored and tested against predictions derived from the models in chapters 3 and 4.

This chapter begins with a brief discussion of the methodology used to collect data, and lists the categories in which information was collected. Then, there is a detailed discussion on the construction of measures. Hypotheses derived from the models in chapters 3 and 4 are then discussed and tested using the data collected. In addition to exploring the relationship between variables, there is also interest in evaluating the key learning assumptions in both models. Recall that the Individual Project Choice and Learning Model in Chapter 3 assumes that learning is constrained in each period. This assumption forces a trade-off in learning between firm-specific and general skills. The Supplier-Firm Project Choice and Learning Model of Chapter 4 relaxes the constraint on learning and instead imposes an increasing-cost-to-learning assumption to obtain learning solutions in each period.

Analysis of the data tends to support the majority of the hypotheses derived from either one model or the other or both. Individuals report that their learning is aligned with the technology emphasis (general or specialized) of their employer firms. Individuals whose projects increase their outside options report greater general learning than other respondents. Individuals
report higher general learning in the presence of higher sharing incentives, but not increased firm-specific learning.

Where predictions from the constrained learning model diverge from the unconstrained model, the data tend to support the unconstrained model. This is interesting since the data set is comprised of responses from individuals. It would appear that the learning assumptions of the constrained model are called into question.

At the firm level, employees in industries that are expected to employ mostly general skills (consulting, network software) do in fact report their learning to be more general than individuals who work for specialized firms (space technology, government contracting, medical technology). Workers at firms where the alternate job prospects are expected to be lower report that their employers use fewer sharing incentives than workers report at firms in the network software and electronics industries which have high worker demand. These results are encouraging because they offer evidence that the incentive and learning measures in the data set are consistent with our assumptions.

**Methodology**

First, a series of exploratory interviews was conducted at firms to guide the development of the analytic models presented above and to develop a survey for more detailed hypothesis testing. A preliminary survey was administered in fall 1997 to test the survey for readability; several overly complex questions were dropped in this phase. Responses from 112 individuals at eight firms were collected from January through March, 1998.
The data collected in this study were not drawn randomly from the population in each firm. Instead, individuals were invited to participate by an insider at each firm and were free to decline. Many of the participants remained anonymous, and all had the option to do so. This was done to improve the veracity of the answers. Data were collected on site at six of the eight firms and via a web survey page at two more firms. The largest number of responses at one firm was 26 while the fewest was 7 at two of the firms. Generalizations to the firm level from these data may not be possible given the small sample sizes. When samples are drawn from a specific group within a firm, that firm is identified by the area in which the sub-group operates. For example, responses were collected from a graphics group within a computer firm. This firm is identified as a graphics operation even though the overall firm’s operations are much more diverse.

A brief profile of each firm, including the types of projects that respondents describe, is given in Appendix D. The next section details some of the interview data that were collected prior to modeling and survey development.

**INTERVIEW DATA**

A series of interviews was conducted to help develop hypotheses, guide model development, and aid in survey development. Excerpts from three of these interviews are shown below to show what kinds of responses people give when asked about project choice and learning.

Data from interviews at one company suggest that the problem of getting engineers to invest in firm-specific technologies is very real. At a small electronics firm, the vice-president of engineering noted that his most
valuable employees are the "maintenance engineers." These engineers are responsible for developing follow-on versions to the company's successful line of print servers. While extremely important to maintaining cash flow and profitability to the firm, the projects generate minimal enthusiasm among the engineering staff, who mostly want to learn the newest technologies. When asked how the maintenance engineers are kept happy, the manager noted that they are "way overpaid" relative to their external opportunities. This is as predicted. When asked about how much project choice the engineers have, the manager said that project choice improved as the employee became more valuable. This last response led to the inclusion of within-firm incentive questions in the survey. Though not modeled analytically, within-firm incentive measures are included in the analysis below.

A second respondent worked at a major computer networking firm in the early 1980s. She joined a team that was supporting a government contract using a computer code that was out of production and little used elsewhere. The respondent wanted to get off the government project because it was a technological dead end. The firm responded with pay and promotion incentives, convincing the person to stay for another year. Finally, the employee left and learned a more mainstream computer language, C, at another company.

A third respondent has worked at several computer software firms. He left one firm in order to learn about networking protocols at another firm. In order to secure a better position, the respondent learned C++ on his own at night. He commented that "if you don't leave, you don't get the raises you deserve." This suggests that the learning in his industry is quite general,

33 Field interview, Geoffrey Parker, November 6, 1997.
34 Field interview, Geoffrey Parker, June 3, 1997.
since his salary generally improved with departures -- so his productivity would be high enough at other firms that they could pay him well.

These interviews, and others, guided the development of the models in Chapters 3 and 4, and the survey data set described below.
# SURVEY DATA SET

## Table 5.1 - Survey Categories and Variables

<table>
<thead>
<tr>
<th>Variables</th>
<th>Project impact on learning</th>
<th>Project impact on opportunities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amount of learning</td>
<td>Overall increase in opportunity</td>
</tr>
<tr>
<td></td>
<td>Type of learning (firm-specific or general)</td>
<td>Increase in internal opportunity, increase in general opportunity</td>
</tr>
<tr>
<td><strong>Background</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td></td>
<td><strong>Project Choice Amount</strong></td>
</tr>
<tr>
<td>Marital status</td>
<td></td>
<td>Number of projects offered</td>
</tr>
<tr>
<td>Children</td>
<td></td>
<td>Amount of project choice</td>
</tr>
<tr>
<td>Education</td>
<td></td>
<td><strong>Project Performance</strong></td>
</tr>
<tr>
<td>Mobility</td>
<td></td>
<td>Adherence to budget</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Adherence to schedule</td>
</tr>
<tr>
<td><strong>Experience</strong></td>
<td></td>
<td><strong>Incentives for project performance</strong></td>
</tr>
<tr>
<td>Years in industry</td>
<td></td>
<td>Bonus payments tied to project success</td>
</tr>
<tr>
<td>Number of firms worked for in industry</td>
<td>Improved project choice in future</td>
<td></td>
</tr>
<tr>
<td>Years at current firm</td>
<td></td>
<td>Better promotion opportunities</td>
</tr>
<tr>
<td>Years in current job</td>
<td></td>
<td>Stock options</td>
</tr>
<tr>
<td><strong>Firm/Industry</strong></td>
<td></td>
<td>Visibility in firm</td>
</tr>
<tr>
<td>Firm</td>
<td></td>
<td><strong>Respondent motivation</strong></td>
</tr>
<tr>
<td>Industry</td>
<td></td>
<td>Advancement in field</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Firm-specific learning</td>
</tr>
<tr>
<td><strong>Firm Technology</strong></td>
<td></td>
<td>General learning</td>
</tr>
<tr>
<td>Longevity of firm’s technology</td>
<td></td>
<td>Job satisfaction</td>
</tr>
<tr>
<td>Uniqueness of firm’s technology</td>
<td></td>
<td>Improvement of outside job opportunities</td>
</tr>
<tr>
<td><strong>Working Environment</strong></td>
<td></td>
<td>Salary</td>
</tr>
<tr>
<td>Work type (process, hardware, software)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Work role (contributor, leader, technical manager, non-technical manager)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Project management (functional, coordinating, heavyweight)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The key sections for hypothesis testing are project impact on learning, project impact on opportunities, incentives for project performance, and the firm's technology. Questions about the respondents firm and industry, background,
experience, and motivation are included to explore other aspects of project-driven learning that are not explicitly modeled.

**CONSTRUCTION OF MEASURES**

Mosteller and Tukey (1977) suggest a strategy of "guided regression" when dealing with a large number of possible explanatory variables in order to pare the number down to a more manageable set. This method is applied to the data set at hand. The survey records about 75 pieces of descriptive, categorical, interval, and ratio information for each respondent. Details and variable summaries are provided in Appendix D. First, each interval and ratio variable is transformed using the Box and Cox power transformation methodology as described in Johnson and Wichern (1998). The goal of this effort is to transform the marginal distributions of the data set to be as close as possible to normal. The next step is to create linear combinations of variables that measure similar concepts. For example, there are five questions that ask about incentives for good project performance (see Table 5.1). By performing a factor analysis, it can be seen how these variables differ from and are related to one another. Most of the variability (69%) is accounted for in the first two of five possible factors.

There is a down-side to the factor approach of creating measures as linear combination of observed variables. We lose a portion of the variance in the original variables whenever we express them in a lower dimension space. Rawlings (1988) warns that important interactions may be lost when creating summary variables in this way. To determine if this is so, Rawlings suggests first factoring the entire data set (of interval and ratio variables) into its orthogonal principal components and regressing the response variables on all of the principal components. There could be components with low eigenvalues that are highly significant in such a regression. Performing this
regression exposes potentially lost information. This is less of a danger in the analysis of the project choice data set at hand because factor analysis is done within theoretically defined categories (learning, incentives, opportunities, and motivation). Nonetheless, a large scale factor analysis was performed to test for the possibility of lost information -- the loss of information was not significant.

Details for each of the measure calculations are given below.

**Incentive Measures**

*Figure 5.1 - Incentive Factor Loadings*

In the figure above, project choice, promotions, and in-firm visibility variables load heavily onto factor 1 while stock options and bonus payment variables load heavily onto factor 2. Factor 1 can be interpreted as summarizing within-firm incentives and factor 2 as the level of sharing incentives (denoted s in the models). This second factor is of particular interest since it represents one of the primary variables under investigation. There is an additional benefit to creating these linear combinations; a set of variables, some highly collinear has been used to create two orthogonal factor
variables that are easy to interpret in terms of the measured variables that load onto them.

By averaging the data within firm groups, the variation of variables by firm can be seen.

Figure 5.2 - Incentive Factors by Firm

In the graph above, observe that employees at the space technology firm, where employees might be expected to have lower outside opportunities, report substantially lower sharing incentives than employees at firms where employees have substantial outside opportunities (software, general computer network interface development).

Learning Measures
In the learning constrained model, the key assumption is that there is a trade-off between firm-specific learning and general learning when modeling the project choices individuals make. In the unconstrained model, no specific relationship between firm-specific learning and general learning is assumed.
The survey asked respondents to report their firm-specific learning and their general learning from their current projects. Responses to these two questions (after power transformation) are plotted below:

Figure 5.3 - Firm-Specific Learning vs. General Learning

Respondents report a significant (p<.02), but small positive correlation between the two variables. There is substantial variability in the amount of learning of any type that respondents report, lending support to the unconstrained model assumption.

A second measure of learning asks respondents to determine how much of their learning would be applicable if they were to move to another firm. This question does not measure the amount of learning, but does capture information about the type of learning.

Measures of firm-specific learning and general learning can be constructed by combining information from the measures discussed above. Using the learning type questions in conjunction with the firm-specific and general
learning questions, measures of both the amount of learning and the type of learning are constructed. A factor analysis using these four variables was performed. The first two factors account for 75% of the variability in the four variables. The variables load onto the factors as follows:

*Figure 5.4 - Learning Factor Loadings*

The two questions about project and cumulative generality of learning load primarily onto factor 1, which can be interpreted as a learning-type factor. Learning is reported to be more general as factor 1 increases. The two learning questions load heavily onto a second factor, which can be interpreted as a learning-amount factor. The factor loadings also preserve the information about type of learning in the firm-specific and general learning questions as follows: The question about the amount of firm-specific learning loads negatively onto factor 1 while the question about the amount of general learning loads positively onto factor 1. In the language of the models in chapters 3 and 4, factor 1 is measuring \(\Delta g - \Delta f\) while factor 2 is measuring \(\Delta g + \Delta f\).
Uncorrelated measures of $\Delta f$ and $\Delta g$ for hypothesis testing are constructed using the learning type and amount factors described above. By adding the learning type and amount factors together and dividing by 2, a measure of $\Delta g$ is recovered. Similarly, a measure of $\Delta f$ is obtained by subtracting the learning type factor from the learning amount factor and dividing by 2.

In the figure below, the firm-specific and general learning measures are plotted by firm averages.

*Figure 5.5 - Learning by Firm*

It is of substantial interest that employees at the firms that focus on space hardware and government IT contracts report the most firm-specific learning, while employees at the information technology consulting firm (who work on-site at customer locations) report the most generally applicable learning. This matches a-priori expectations and gives some confidence that the measures are moving in the proper direction. By construction, there is no correlation between the constructed firm-specific and general learning measures at the individual level.\(^{35}\) However, there is a negative correlation

\(^{35}\) There is a potential problem using uncorrelated measures of firm-specific and general learning.
between averages of firm-specific learning and general learning which are aggregated at the firm level.

**Outside Options Measures**

Respondents are asked to report how much each project contributes to their internal opportunities and to their external opportunities. The answers to each question are positively correlated, as shown below, suggesting that projects differ more in their total impact on opportunities than on the type of opportunity.

*Figure 5.6 Project Impact on Internal Opportunities vs. External Opportunities*

![Graph showing project impact on internal vs. external opportunities](image)

In order to construct separate measures of the total increase in opportunities versus the type of opportunity, a factor analysis of the two opportunity variables is performed. Each variable loads onto each factor as follows:

---

Learning. Correlations of the underlying variables in the factor analysis to explanatory variables may be lost after the factor transformation. Regression results are reported for both the constructed variables and for the underlying variables.
In the figure above, both opportunity variables load heavily onto factor 1. This factor can be interpreted as measuring the amount of increase in opportunities both inside and outside the firm. The two questions load onto factor 2 in opposite signs. This factor can be interpreted as measuring the difference between outside and inside opportunities.

By taking sums and differences, the values for internal and outside opportunity improvement can be recovered. Outside opportunity improvement is taken as the sum of factor 1 and factor 2. Inside opportunity improvement is taken as the difference between factor 1 and factor 2. The increase in outside opportunity may be interpreted as a measure for $\beta_c$.

The figure below plots firm averages for each opportunity type.
Employees at the space technology firm report opportunity increases as mostly internal, while employees at the network software and IT consulting firms report large external opportunity changes.

Motivation Measures
Though not explicitly used in the models and hypothesis testing, a series of questions about what motivates people was asked at five of the firms in the study. As with the other measures, the motivation measure is created by applying a principal-component factor analysis on the six motivation variables (firm-specific learning, salary, job satisfaction, general learning, outside job opportunities, and advancement in field). The first two factors account for 62% of the variability in the six variables. Factor loadings and firm plots are shown below.
In the figure above, factor 1 can be interpreted as an outside-oriented motivation factor. Motivation by advancement in field, improved outside job opportunities, and general learning load heavily on factor 1. Motivation by firm-specific learning and salary load heavily onto factor 2, which can be interpreted as a firm-oriented motivation factor. The variables split out as expected, except for job satisfaction motivation which loads onto both factors in roughly equal amounts.
Note that motivation responses are reported for only five firms. This questions category was added after the first three firms had been surveyed. In this figure, observe that employees at the IT consulting firm report high external motivation and low within-firm motivation, while employees at the space technology firm report low external motivation but high within-firm motivation.

**Technology Measures**

Two technology measures are used in the analysis below. The first is a measure of the uniqueness of the technology employed by the firm. Respondents were asked to rank how specialized the technologies employed by their firm are relative to other firms in their industry. The second measure assesses how rapidly the technologies used by respondents are changing. Each respondent was asked what the four most important technologies they use are. They were then asked to estimate how long learning about those technologies remains relevant. The average of the four numbers was transformed to normality through a power transformation function. This gives us a measure of technological change. The figure below plots the average responses from each firm against these two measures.
In the figure above, the space hardware firm is an outlier in both technology uniqueness and lifetime. This is expected. The firm that supplies commercial and government satellite telecommunications equipment also reports substantial technology specificity. Again, the IT consulting firm reports the lowest technology specificity. The network technology firm reports minimal specificity and the fastest turnover of all the industries represented. This is also consistent with our view of the rapidly changing internet software services market.

In the next section, we show the relationships between individual learning, incentives, firm technology, and opportunities along with predictions for these relationships derived from the models in chapters 3 and 4.\textsuperscript{36}

\textsuperscript{36} Hypotheses derived from the models assume $s_1 = s_2$ and $k_f = k_g = 1$. 

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**Expected Relationships & Results**

Hypotheses for firm-specific learning are presented first, followed by general learning hypotheses, then sharing hypotheses. Separate hypotheses are shown for the learning constrained model (Chapter 3) and the unconstrained learning model (Chapter 4). Results refer to hypothesis tests performed using the constructed (factor analysis) measures of firm-specific and general learning. The regression results in a later section below test relationships between all of the learning and incentive variables with a number of independent variables.

**Firm-Specific Learning Hypotheses**

Firm-Specific Learning ($\Delta f$) relation to firm technology ($\alpha, \beta$)

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Constrained Model</th>
<th>Unconstrained Model</th>
<th>Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H1a,b$</td>
<td>Increases</td>
<td>Increases</td>
<td>$\left( \frac{\partial (\Delta f_i)}{\partial \alpha} &gt; 0 \right)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\left( \frac{\partial (\Delta f_i)}{\partial \alpha} &gt; 0 \right)$</td>
</tr>
<tr>
<td>$H2a,b$</td>
<td>Decreases</td>
<td>No Effect</td>
<td>$\left( \frac{\partial (\Delta f_i)}{\partial \beta} &lt; 0 \right)$</td>
</tr>
</tbody>
</table>

Both models lead to a prediction that individual firm-specific learning increases as the firm employs more firm-specific technology. The individual model predicts that firm-specific learning falls as the firm uses more general technology while the supplier-firm model predicts no effect.

These hypotheses cannot be tested individually because the measure of technology uniqueness does not distinguish between levels of $\alpha$ and $\beta$. Instead, technology uniqueness can be interpreted as measuring the difference
between $\alpha$ and $\beta$. The data support at least one of the hypotheses and could support as many as three of the hypotheses.

### Firm-Specific Learning ($\Delta f$) relation to outside opportunities ($\beta_c$)

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Constrained Model</th>
<th>Unconstrained Model</th>
<th>Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>H3a,b</td>
<td>Decreases (\frac{\partial (\Delta f_1)}{\partial \beta_c} &lt; 0)</td>
<td>No effect (\frac{\partial (\Delta f_1)}{\partial \beta_c} = 0)</td>
<td>Insignificant</td>
</tr>
</tbody>
</table>

The data support the unconstrained (supplier firm) model prediction (H3b) of no effect between $\Delta f$ and $\beta_c$.

### General Learning Hypotheses

#### General Learning ($\Delta g$) relation to firm technology ($\alpha, \beta$)

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Constrained Model</th>
<th>Unconstrained Model</th>
<th>Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>H4a,b</td>
<td>Decreases (\frac{\partial (\Delta g_1)}{\partial \alpha} &lt; 0)</td>
<td>No Effect (\frac{\partial (\Delta g_1)}{\partial \alpha} = 0)</td>
<td>$\frac{\partial (\Delta g)}{\partial (\alpha - \beta)}$ Insignificant</td>
</tr>
<tr>
<td>H5a,b</td>
<td>Increases (\frac{\partial (\Delta g_1)}{\partial \beta} &gt; 0)</td>
<td>Increases (\frac{\partial (\Delta g_1)}{\partial \beta} &gt; 0)</td>
<td>$\frac{\partial (\Delta g)}{\partial (\alpha - \beta)}$ Insignificant</td>
</tr>
</tbody>
</table>

The constrained learning model predicts that general learning falls as a function of the firm's increased use of specialized technology while the unconstrained supplier firm model predicts no effect. Both models predict that general learning increases in a firm’s use of general technologies.

Again, these hypotheses cannot be tested individually because the measure of technology uniqueness does not distinguish between levels of $\alpha$ and $\beta$, but
instead measures \((\alpha - \beta)\). The data analysis does not suggest a significant relationship between \(\Delta g\) and \((\alpha - \beta)\). This result could support H4b. H4a, H5a, and H5b are not supported by the data.

General Learning \((\Delta g)\) relation to outside opportunities \((\beta_c)\)

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Constrained Model</th>
<th>Unconstrained Model</th>
<th>Evidence</th>
</tr>
</thead>
</table>
| H6a,b      | \[
\left( \frac{\partial (\Delta g_1)}{\partial \beta_c} > 0 \right) \]
| Increases  | \[
\left( \frac{\partial (\Delta g)}{\partial \beta_c} > 0 \right) \]
| Increases  | \[
\left( \frac{\partial (\Delta g)}{\partial \beta_c} > 0 \right) \]|

Both models predict that general learning is positively correlated outside opportunities. The data support these predictions.

Ideally, the effect of different sharing levels on firm-specific and general learning would be tested. However, to do so requires an instrumental variable for sharing in order to perform a two-stage least squares regression.\(^{37}\) Since such an instrument variable is not available, hypotheses are constructed for how the sharing levels vary with other parameters of the model \((\alpha, \beta, \beta_c)\). Details on the calculation of these hypotheses appear in Appendix A (for the constrained model) and Appendix B (for the unconstrained model).

\(^{37}\) A LISREL model could also be used if an instrument for \(s\) were available.
Incentives Hypotheses

Sharing (s) relation to firm technology (α,β)

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Constrained Model</th>
<th>Unconstrained Model</th>
<th>Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>H7a,b</td>
<td>Indeterminate</td>
<td>Indeterminate</td>
<td>$\frac{\partial s}{\partial (\alpha - \beta)}$ Insignificant</td>
</tr>
<tr>
<td>H8a,b</td>
<td>Decreases</td>
<td>Decreases</td>
<td>$\frac{\partial s}{\partial (\alpha - \beta)}$ Insignificant</td>
</tr>
</tbody>
</table>

The models do not generate consistent predictions for how the sharing levels vary with firm proprietary technology, α. The values of other parameters can drive the derivative positive or negative. The prediction that s falls in β is drawn from simulation in the constrained model since there is no global analytic solution. In the unconstrained model, the sharing incentive falls in β for $\beta, < 2\beta$. The data is inconclusive on how each of the incentive measures varies with firm technology.

Sharing (s) relation to competitor general technology (βc)

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Constrained Model</th>
<th>Unconstrained Model</th>
<th>Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>H9a,b</td>
<td>Increases</td>
<td>Increases</td>
<td>Increases</td>
</tr>
</tbody>
</table>

The derivative coefficients are positive, but have minimal significance (.218, .252).

Again, simulation is used in the constrained model to generate the prediction that incentives increase in the competitor’s ability to use general capabilities.
The unconstrained model also predicts that incentives increase in $\beta_i$. The regression coefficients on both sharing variables are positive, but have a large possibility of being zero.

**Discussion of Hypotheses**

The data support many of the hypotheses tested. Where there is conflict between predictions from the constrained model versus the unconstrained model (H2, H3, H4) the data are silent or tend to support the unconstrained model. The key assumption of the constrained model is that learning in each period is limited and that individuals are on the learning frontier, forcing a trade-off between firm-specific and general learning. In fact, the data suggest that people are not operating on a frontier, since we saw above that they do not report a trade-off between firm-specific learning and general learning. This fits the assumptions of the unconstrained model where there is no limit on supplier firm learning in each period.

**Regression Results**

Regressions are shown for learning variables ($\Delta f, \Delta g$, raw firm-specific learning, raw general learning, generality of learning) and incentive variables (internal incentives and tangible incentives). For each dependent variable, the first model tests only the variable's relationship to the variables ($\alpha, \beta, \beta_i$) which appear in the hypotheses. Two additional independent variables (internal opportunities, firm technology lifetime) are entered into the next two models for each dependent variable. The within-firm models include a dummy variable for each firm to control for between-firm effects. The tests are repeated using firm averages (n=8) to test directly for between-firm effects.
Table 5.2 - Firm-Specific Learning Regression Models - Constructed Variable

Dependent Variable: Firm-specific learning (constructed variable $\Delta f$)

<table>
<thead>
<tr>
<th></th>
<th>Within firms</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model 1</td>
<td>Model 2</td>
<td>Model 3</td>
<td>Model 4</td>
<td>Model 5</td>
<td>Model 6</td>
<td></td>
</tr>
<tr>
<td>Opportunities Outside Firm ($\beta$)</td>
<td>.070 (0.461)</td>
<td>.069 (0.454)</td>
<td>.078 (0.400)</td>
<td>-.302 (0.723)</td>
<td>-.458 (0.701)</td>
<td>-.898 (0.467)</td>
<td></td>
</tr>
<tr>
<td>Firm Technology Uniqueness ($\alpha$-$\beta$)</td>
<td>.151 (0.003)</td>
<td>.156 (0.002)</td>
<td>.156 (0.001)</td>
<td>.058 (0.755)</td>
<td>.019 (0.943)</td>
<td>.077 (0.773)</td>
<td></td>
</tr>
<tr>
<td>Opportunities Inside Firm</td>
<td>.257 (0.007)</td>
<td>.284 (0.003)</td>
<td></td>
<td>.124 (0.823)</td>
<td></td>
<td>1.000 (0.316)</td>
<td></td>
</tr>
<tr>
<td>Firm Technology Lifetime</td>
<td></td>
<td></td>
<td>.077 (0.095)</td>
<td></td>
<td>.342 (0.289)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R^2$</td>
<td>.220</td>
<td>.277</td>
<td>.301</td>
<td>.258</td>
<td>.268</td>
<td>.528</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>2.731</td>
<td>3.339</td>
<td>3.372</td>
<td>.867</td>
<td>.488</td>
<td>.839</td>
<td></td>
</tr>
<tr>
<td>d.f. (residual)</td>
<td>97</td>
<td>96</td>
<td>94</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

Firm dummies are included in models 1, 2, 3
Firm averages are used in models 4, 5, 6

Hypotheses are tested using Model 1. In model 2, within-firm opportunities are added to the regression. This term has a significant positive effect on the predicted values for $\Delta f$. In model 3, firm technology lifetime is added to the regression. This term has a moderately significant negative effect on predicted values of $\Delta f$. Models 4, 5, and 6 repeat the first three models using firm average values. No significant relationships are found in the between-firms models.38

The next set of regression models explore the relationship between each of the independent variables under study and the raw measure of firm-specific learning taken directly from the survey results.

---

38 Recall that there are only eight firms tested in the between-firms model.
Table 5.3 - Firm-Specific Learning Regression Models - Raw Variable

<table>
<thead>
<tr>
<th></th>
<th>Within firms</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model 1</td>
<td>Model 2</td>
<td>Model 3</td>
<td>Model 4</td>
<td>Model 5</td>
<td>Model 6</td>
</tr>
<tr>
<td>Opportunities Outside Firm (βr)</td>
<td>.770  (.019)</td>
<td>.764  (.013)</td>
<td>.793  (.010)</td>
<td>1.179  (.510)</td>
<td>.430  (.855)</td>
<td>-.375  (.879)</td>
</tr>
<tr>
<td>Firm Technology Uniqueness (α−β)</td>
<td>.221  (.192)</td>
<td>.249  (.114)</td>
<td>.245  (.121)</td>
<td>.292  (.458)</td>
<td>.105  (.847)</td>
<td>.208  (.705)</td>
</tr>
<tr>
<td>Opportunities Inside Firm</td>
<td>1.254  (.000)</td>
<td>1.286  (.000)</td>
<td></td>
<td>.595  (.596)</td>
<td>2.205  (.295)</td>
<td></td>
</tr>
<tr>
<td>Firm Technology Lifetime</td>
<td>-.170  (.262)</td>
<td></td>
<td></td>
<td>-.625  (.341)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

R²  | .124  | .256  | .261  | .115  | .182  | .426  |
F    | 1.375 | 2.078 | 2.711 | .324  | .297  | .556  |
d.f. (residual)  | 97    | 96    | 94   | 5     | 4     | 3     |

Firm dummies are included in models 1, 2, 3
Firm averages are used in models 4, 5, 6

In the models above, significantly positive relationships are found within firms between reported firm-specific learning and outside opportunities, firm technology uniqueness, and internal opportunities. No significant between-firm relationships are observed. The major difference between the constructed measure of firm-specific learning and the raw measure is that outside opportunities are significantly related to the raw measure of firm-specific learning, while they are not significantly related to the constructed measure. In the raw data, firm-specific learning and opportunities are significantly correlated. Factor analysis on both learning and opportunities creates factors in which the firm-specific learning factor is not correlated to one of the opportunity measures (outside opportunities), but strongly correlated to internal opportunities. Understanding the relationships between raw variables is important to understanding how the orthogonal factor variables are related.

The next set of regressions tests the constructed general learning variable (Ag) against the independent variables.
### Table 5.4 - General Learning Regression Models - Constructed Variable

**Dependent Variable:** General learning (constructed variable Δg)

<table>
<thead>
<tr>
<th></th>
<th>Within firms</th>
<th>Between firms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model 1</td>
<td>Model 2</td>
</tr>
<tr>
<td>Opportunities Outside Firm (β_o)</td>
<td>.633 (.000)</td>
<td>.632 (.000)</td>
</tr>
<tr>
<td>Firm Technology Uniqueness (α-β)</td>
<td>.008 (.856)</td>
<td>.014 (.708)</td>
</tr>
<tr>
<td>Opportunities Inside Firm</td>
<td>.312 (.000)</td>
<td>.315 (.000)</td>
</tr>
<tr>
<td>Firm Technology Lifetime</td>
<td>-.014 (.702)</td>
<td>.100 (.600)</td>
</tr>
</tbody>
</table>

R^2 | .452 | .536 | .537 | .605 | .776 | .799
F  | 8.009 | 10.075 | 9.069 | 3.835 | 4.624 | 2.982
d.f. (residual) | 97 | 96 | 94 | 5 | 4 | 3

Firm dummies are included in models 1, 2, 3
Firm averages are used in models 4, 5, 6

The first model is a direct test of model hypotheses -- significantly positive relationships are found between Δg and both test variables. General learning is positively related to outside opportunities. In model 3, internal opportunities are also positively related to general learning. In the between-firms tests, the regressions are not significant.

The next set of regressions tests the raw general learning variable as reported in the surveys.
Table 5.5 - General Learning Regression Models - Raw Variable

Dependent Variable: General Learning (raw measure)

<table>
<thead>
<tr>
<th></th>
<th>Within firms</th>
<th>Between firms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model 1</td>
<td>Model 2</td>
</tr>
<tr>
<td>Opportunities Outside Firm (β,)</td>
<td>1.791 (0.000)</td>
<td>1.786 (0.000)</td>
</tr>
<tr>
<td>Firm Technology Uniqueness (α−β)</td>
<td>0.088 (0.572)</td>
<td>0.110 (0.452)</td>
</tr>
<tr>
<td>Opportunities Inside Firm</td>
<td>1.023 (0.001)</td>
<td>1.088 (0.000)</td>
</tr>
<tr>
<td>Firm Technology Lifetime</td>
<td>.169 (0.231)</td>
<td>.034 (0.949)</td>
</tr>
</tbody>
</table>

R² | .331 | .410 | .421 | .037 | .817 | .817 |
F | 4.801 | 6.068 | 5.690 | .097 | 5.942 | 3.349 |
d.f. (residual) | 97 | 96 | 94 | 5 | 4 | 3 |

Firm dummies are included in models 1, 2, 3
Firm averages are used in models 4, 5, 6

The results from the raw general learning regressions are the same as the constructed general learning variable except for model 5, one of the between-firm models. Unexpectedly, model 5 shows a negative relationship between general learning and outside opportunities. This result directly contradicts model predictions and observed relationships for within-firm tests.

Interestingly, model 5 also shows a negative relationship between firm technology uniqueness and general learning. Both the constrained and unconstrained models predict $\partial Dg > 0$ and are consistent with this regression result.\(^{39}\)

The next set of regressions explores relationships between the independent variables and the cumulative-generality-of-learning variable.

---

\(^{39}\) Recall that the technology uniqueness variable can be interpreted as (α−β), so the expected sign of the relationship between Δg and β is reversed.
Table 5.6 - Cumulative-generality-of-Learning Regression Models

<table>
<thead>
<tr>
<th></th>
<th>Within firms</th>
<th></th>
<th>Between firms</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model 1</td>
<td>Model 2</td>
<td>Model 3</td>
<td>Model 4</td>
</tr>
<tr>
<td>Opportunities Outside Firm (βᵢ)</td>
<td>0.049</td>
<td>0.049</td>
<td>0.048</td>
<td>0.086</td>
</tr>
<tr>
<td></td>
<td>(0.017)</td>
<td>(0.018)</td>
<td>(0.020)</td>
<td>(0.576)</td>
</tr>
<tr>
<td>Firm Technology Uniqueness (α-β)</td>
<td>-0.030</td>
<td>-0.030</td>
<td>-0.030</td>
<td>-0.027</td>
</tr>
<tr>
<td></td>
<td>(0.005)</td>
<td>(0.005)</td>
<td>(0.005)</td>
<td>(0.428)</td>
</tr>
<tr>
<td>Opportunities Inside Firm</td>
<td>0.010</td>
<td>0.007</td>
<td></td>
<td>0.022</td>
</tr>
<tr>
<td></td>
<td>(0.630)</td>
<td>(0.752)</td>
<td></td>
<td>(0.826)</td>
</tr>
<tr>
<td>Firm Technology Lifetime</td>
<td></td>
<td></td>
<td>0.008</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.417)</td>
<td></td>
</tr>
<tr>
<td>R²</td>
<td>0.267</td>
<td>0.269</td>
<td>0.277</td>
<td>0.598</td>
</tr>
<tr>
<td>F</td>
<td>3.537</td>
<td>3.212</td>
<td>2.995</td>
<td>3.717</td>
</tr>
<tr>
<td>d.f. (residual)</td>
<td>97</td>
<td>96</td>
<td>94</td>
<td>5</td>
</tr>
</tbody>
</table>

Firm dummies are included in models 1, 2, 3
Firm averages are used in models 4, 5, 6

Model 1 shows a significantly positive relationship between cumulative-generality-of-learning and outside opportunities while showing a negative relationship between generality of learning and technology uniqueness. These relationships are consistent with the model hypotheses presented above. Internal opportunities and technology lifetime are not reported to have a significant relationship to the cumulative-generality-of-learning. None of the between-firm models are significant.

Incentives are explored in the next two sets of regressions.
Table 5.7 - Within-firm Incentive Regression Models-constructed variable

<table>
<thead>
<tr>
<th>Dependent Variable: Within-firm incentives (promotions, visibility, project choice)</th>
<th>Within firms</th>
<th>Between firms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model 1</td>
<td>Model 2</td>
</tr>
<tr>
<td>Opportunities Outside Firm (β,)</td>
<td>.180</td>
<td>.190</td>
</tr>
<tr>
<td></td>
<td>(.218)</td>
<td>(.186)</td>
</tr>
<tr>
<td>Firm Technology Uniqueness (α-β)</td>
<td>.018</td>
<td>.021</td>
</tr>
<tr>
<td></td>
<td>(.816)</td>
<td>(.775)</td>
</tr>
<tr>
<td>Opportunities Inside Firm</td>
<td>.311</td>
<td>.312</td>
</tr>
<tr>
<td></td>
<td>(.035)</td>
<td>(.036)</td>
</tr>
<tr>
<td>Firm Technology Lifetime</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

R² | .149 | .191 | .191 | .090 | .597 | .597 |
F  | 1.579| 1.911| 1.732| .248| 1.974| 1.111|
d.f. (residual) | 90 | 89 | 88 | 5 | 4 | 3 |

Firm dummies are included in models 1, 2, 3
Firm averages are used in models 4, 5, 6

The only significant relationship found in the models above is a positive relationship between within-firm incentives and within-firm opportunities. Though the models do not include the inside opportunity construct, it is consistent that internal opportunities and internal incentives to perform well should move together.

The next set of regressions explores the relationship of the independent variables to tangible incentives.
Table 5.8 - Tangible Incentive Regression Models-constructed variable

<table>
<thead>
<tr>
<th></th>
<th>Within firms</th>
<th>Between firms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model 1</td>
<td>Model 2</td>
</tr>
<tr>
<td>Opportunities Outside Firm (β,₁)</td>
<td>.140</td>
<td>.146</td>
</tr>
<tr>
<td></td>
<td>(.252)</td>
<td>(.230)</td>
</tr>
<tr>
<td>Firm Technology Uniqueness (α–β)</td>
<td>-0.084</td>
<td>-0.082</td>
</tr>
<tr>
<td></td>
<td>(.185)</td>
<td>(.193)</td>
</tr>
<tr>
<td>Opportunities Inside Firm</td>
<td>.187</td>
<td>.184</td>
</tr>
<tr>
<td></td>
<td>(.130)</td>
<td>(.142)</td>
</tr>
<tr>
<td>Firm Technology Lifetime</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

R² | .388      | .404      | .404      | .272      | .565      | .566      |
F  | 5.709     | 5.480     | 4.975     | .935      | 1.729     | .979      |

d.f. (residual) | 90        | 89        | 88        | 5         | 4         | 3         |

Firm dummies are included in models 1, 2, 3
Firm averages are used in models 4, 5, 6

The firm dummies explain a substantial amount of the variability in the within-firm regressions. The sign of the relationship between outside opportunities and tangible incentives is positive as expected, but there is a large probability that there is no relationship. Interestingly, the most significant relationship is between internal opportunities and tangible incentives (p<.15). People who report that their project substantially improve in-firm opportunities also report that they receive bonuses or stock options. The between-firm regressions are not significant.

**Comments on Empirical Results**

Overall, the empirical results are less consistent with the learning assumptions in the constrained learning model than they are with the learning assumptions in the constrained model. This suggests that future
empirical work in this area should include more tests of the form of learning
and what the costs of learning are to individuals.

The next chapter considers some implications of the project choice and
learning research presented in this thesis.
6. DISCUSSION

This thesis presents two models and a data set which help to explore the interplay between firm and industry technologies, incentives, and the learning investments individuals make. The models contribute to the literature by making reservation wages endogenous and technology dependent. The first model assumes that individuals are constrained in their ability to build capabilities in each period and that most projects differ by type of learning, but not by amount. The second model relaxes this learning constraint and imposes increasing costs to learning to allow for project choice solutions.

Both models predict, and the data support, that individuals align their learning with their employer's technologies. The models also predict that higher general learning is associated with higher (external) valuations to that learning. The data support these predictions. The constrained model predicts that firm-specific learning falls in higher valuations to general learning, while the unconstrained model makes no prediction. There is no relation between firm-specific learning and the outside valuation of general learning seen in the data. Finally, the models suggest that sharing should increase in the outside valuation of general learning. The data weakly support this prediction.

IMPLICATIONS FOR SKILLED EMPLOYEE LEARNING AND RETENTION

The model results call attention to effect labor market competitors might have on employee skill development. To the extent that employees shift skill development to improve their job options, they may be under-investing in a firm's proprietary technology. Even if they don't shift resources away from
firm technologies, they can make extra skill investments in an effort to raise their outside value.

This issue is especially important for firms whose employees discover job options in different industries. One durable goods manufacturer which employs programmers in the midwest has been losing valuable skilled employees to Silicon Valley firms who are willing to pay much higher salaries than the prevailing wages at the firm.\textsuperscript{40} The company has recently changed its employee contract practices in response to this loss, but not before many people left the company. A skills-based understanding of where labor market competition was going to come from might have allowed the firm to respond more quickly.

**Implications for Competency Driven Supply Chain Design**

This investigation began with the goal of examining a core issue in supply-chain design: how can firms manage competence creation in their suppliers (internal or external) to their benefit? The goal behind answering this question is to help firms think about what types of suppliers to choose to be supply chain members, and how to manage the creation of capability in the supply chain over time. The choice of supplier type cannot be made independently of the type of relationship firms wish to have with their supplier -- from arm's length to vertically integrated. This work cannot answer these questions definitively, but it does provide a framework for thinking about these important issues.

Projects are a natural unit of analysis for which to analyze these issues. Projects represent technologically-driven re-contracting points; whether or

\textsuperscript{40} Telephone interview, Geoffrey Parker, April 14, 1998.
not parties wish to take action at the end of a project, something must happen. Capabilities must be re-evaluated, project choices must be generated, and the choice of a new project or termination of the relationship must be made.

Projects change both parties to the relationship. The firm may no longer be able to work in the same way with agents who have developed highly valuable general skills. A closely directed relationship can cease to be appropriate for highly skilled suppliers. These suppliers will want to capture the product of their expertise. They can do this by changing associations, and working with a firm which can better use the capabilities they have gathered, or they might choose to become more independent and seek to capture returns to their expertise more directly in the market.

This last observation could provide an explanation for the evolution of suppliers from the “build-to-print” type to “black-box” type as described by Asanuma (1989). For example, a lower-skilled supplier might initially take detailed direction from the firm in the form of exact specifications for products to build, and build firm-specific capabilities in producing the firm’s products. As this supplier develops capabilities, it might become expert in designing products for its internal production system. If the firm were not able to take advantage of this skill, the supplier could do better by working with another firm which was poised to take advantage of this new capability in product development. Alternatively, a customer firm might have multiple ways of working with suppliers. As suppliers evolve, the relationship between customer and supplier can also evolve so that the supplier’s skills are always well utilized.

To make this example more concrete, consider the relationship between Nippondenso, an automobile parts supplier, and its long-time customer, Toyota. Over time, Nippondenso grew the capability to supply integrated
systems (radiators and alternators for example) to Toyota and gained control 
over many lower level elements of product design -- being required to meet 
high level system specifications instead of building parts to detailed drawings 
(Whitney, 1993). Nippondenso product development engineers learned to 
work closely with their process engineer colleagues to design products which 
can be manufactured with high quality and low cost. Toyota is used to 
working with Nippondenso and does not need to duplicate the product 
design resources which reside at the supplier.

For many years, Toyota was unique in being able to take advantage of 
Nippondenso's product design and manufacturing capabilities. In recent 
years, however, Chrysler has begun to work with Nippondenso in a similar 
way - issuing higher level system specifications, while letting Nippondenso 
design the detailed parts to mate with Nippondenso's production system.41 
As a result, the relationship between Toyota and Nippondenso has changed. 
Nippondenso, as well as other large suppliers to Japanese automobile 
companies, has developed a large, fast-growing business among European 
and U.S. automobile assembler companies (Fine, 1996). In previous decades, 
Toyota developed long-term relationships with it tier 1 suppliers. In recent 
years, as a result of the growth of suppliers like Nippondenso, Toyota's 
relationship with its supply base has become more fluid (Fine, 1996). In effect, 
Chrysler (and other companies) has expanded Nippondenso's set of outside 
opportunities by developing the capability to take advantage of 
Nippondenso's skills. In terms of the models presented above, Chrysler has 
raised the $\beta_s$ in Toyota's profit function. Looked at another way, some of the 
Nippondenso Toyota firm-specific knowledge which Toyota used to enjoy has 
become general knowledge which has value to other companies.

This line of research encourages firms to think about a supply chain of capabilities and where to grow capabilities along the chain. While the model does not explicitly model make versus buy issues, it does provide a way to think about capability growth in the supply chain as a result of repeated interaction. If a firm identifies a capability in the chain which will become increasingly important, then the firm can move to protect its access to that information. This provides a significantly different view of purchasing than the practice at some companies which treats each interaction with suppliers as a separate event and pays no attention to longer term knowledge accumulation.
7. RESEARCH AGENDA AND EXTENSIONS

There are a rich set of avenues to explore, building upon the models and data presented in this thesis. These include, but are not limited to:

- Individual learning
- Firm learning
- Output uncertainty
- Agent differentiation (in learning rate)
- Multiple firms/suppliers
- Supplier firm data set

INDIVIDUAL LEARNING

The results from the empirical analysis in Chapter 5 suggest that a fruitful avenue of inquiry would be to explore the paths of learning in response to incentives and costs. In each of the models, an assumption was made about the form of learning, constrained or unconstrained. The data better support hypotheses developed from the unconstrained model. It would be valuable for future modeling efforts to have a clearer empirical view of the learning function.

FIRM LEARNING

Early in the paper, it was observed that projects change both agents and firms. So far, only the change to agent capabilities has been modeled. Allowing $\alpha$ and $\beta$ to become functions of project choice as well as $f$ and $g$ would allow for a richer set of firm strategies. Firms may better tolerate outside-oriented
projects since they might also improve the firm’s ability to make use of general skills created by the project. Similarly, firms may see a doubly positive impact from internally oriented projects as their ability to make use of an agent’s specialized skills improves.

**OUTPUT UNCERTAINTY**

Currently, the models are deterministic. To add uncertainty to the model, output could be modeled as a function of agent capability plus a noise term. The noise surrounding firm-specific output could be larger than that for general production, reflecting the narrower base on which this output is produced. If the agent is risk-averse, the degree of output uncertainty could be important in the agent’s payoff calculation.

**AGENT DIFFERENTIATION**

Currently, the agents get to make most of the choices - they choose projects and they either stay at a firm or leave. This thesis currently models the interaction of firms with suppliers who have market power as a result of their accumulation of firm-specific capabilities.

**MULTIPLE FIRMS/SUPPLIERS**

Multiple agents could be introduced, where agents are differentiated by their initial capability stocks, and their learning rates (different for firm-specific and general capital). Firms might choose to work with agents who have low initial capability stocks, but high learning potential. There should be a sorting
out of firms and agents to achieve the best match of agent learning rates and firm technologies. Jovanovic (1979a) offers a point from which to begin such an extension.

**SUPPLIER FIRM DATA SET**

Finally, it would be valuable to collect data on the behavior of supplier firms in response to customer (current and potential) technologies to complement the data set in this thesis which was collected from individuals. The decision to have individual respondents came about largely as a matter of experience given the longer time periods associated with lining up multiple firm participants.
REFERENCES


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APPENDIX A

INDIVIDUAL (CONSTRAINED LEARNING) MODEL ANALYSIS DETAILS

\[ y_1 = \alpha \Delta f_1 + \beta \sqrt{1 - \Delta f_1^2} \]
\[ y_2 = \alpha (\Delta f_1 + \Delta f_2) + \beta (\sqrt{1 - \Delta f_1^2} + \sqrt{1 - \Delta f_2^2}) \]
\[ y_2^c = \alpha_c (\Delta f_2) + \beta_c (\sqrt{1 - \Delta f_1^2} + \sqrt{1 - \Delta f_2^2}) \]

Central Planning (First Best)

Central planning problem: \( \max_{\Delta f_1, \Delta f_2} (y_1 + y_2) \)

Where \( y_1 \) and \( y_2 \) are defined above, the first-order conditions for maximum output are:

\[ \Delta f_1 \text{ (Central)} = \frac{\alpha}{\sqrt{\alpha^2 + \beta^2}}, \Delta f_2 \text{ (Central)} = \frac{\alpha}{\sqrt{\alpha^2 + \beta^2}} \]

The Hessian matrix of output with respect to \( \Delta f_1, \Delta f_2 \) is:

\[
\begin{pmatrix}
-\frac{2 \beta \Delta f_1^2}{(1 - \Delta f_1^2)^{1/2}} & -\frac{2 \beta}{\sqrt{1 - \Delta f_1^2}} \\
0 & -\frac{\beta \Delta f_2^2}{(1 - \Delta f_2^2)^{1/2}} - \frac{\beta}{\sqrt{1 - \Delta f_2^2}}
\end{pmatrix}
\]

Sharing

Individual's problem:

\[
\max_{\Delta f_1} \left( (1 - s_1) r_1 + \max_{\Delta f_2} \left( \max((1 - s_2) y_2^c) + s_1 y_1 + \max_{\Delta f_2} (s_2 y_2) \right) \right)
\]

\[ \Delta f^*_1 = \frac{(s_1 + s_2) \alpha}{\sqrt{(\alpha^2 + \beta^2)s_1^2 + 2s_2(\beta - \beta_c)\beta_c + \beta_c^2 + s_2^2(\alpha^2 + \beta^2 - 2\beta\beta_c + \beta_c^2) + 2s_1(\beta\beta_c + s_2(\alpha^2 + \beta^2 - \beta_c))}} \]
Comparative Statics:

$$\partial_{\mu} \Delta f^* > 0$$

$$\partial_{\tau} \Delta f^* = \frac{\alpha (-1 + s_2) (\mu_1 + s_2) \beta_c (-\beta (\mu_1 + s_2) + (1 + s_2) \beta_c)}{\sqrt{(\mu_1 + s_2)^2 + (\alpha^2 + \beta^2)(\mu_1 + s_2)^2 - 2 \beta (-1 + s_2) (\mu_1 + s_2) \beta_c + (-1 + s_2)^2 \beta_c^2})^{3/2}}$$

$$\partial_{\tau} \Delta f^* > 0$$

$$\partial_{\beta} \Delta f^* = \frac{\alpha (1 + s_1) (\mu_1 + s_2) \beta_c (\beta \mu_1 + s_2 (\beta - \beta_c) + \beta_c)}{\sqrt{(\mu_1 + s_2)^2 + (\alpha^2 + \beta^2)(\mu_1 + s_2)^2 - 2 \beta (-1 + s_2) (\mu_1 + s_2) \beta_c + (-1 + s_2)^2 \beta_c^2})^{3/2}}$$

$$\partial_{\alpha} \Delta f^* > 0$$

$$\partial_{\alpha} \Delta f^* = \frac{\sqrt{(\mu_1 + s_2)^2 + (\beta \mu_1 + s_2 (\beta - \beta_c) + \beta_c)^2}}{(\alpha^2 + \beta^2)(\mu_1 + s_2)^2 - 2 \beta (-1 + s_2) (\mu_1 + s_2) \beta_c + (-1 + s_2)^2 \beta_c^2})^{3/2}}$$

$$\partial_{\beta} \Delta f^* < 0$$

$$\partial_{\beta} \Delta f^* = \frac{- (\alpha (s_1 + s_2) \sqrt{(s_1 + s_2)^2 + (\beta s_1 + s_2 (\beta - \beta_c) + \beta_c)^2}}}{(\alpha^2 + \beta^2 s_2 (\beta - \beta_c) \beta_c + \beta_c^2 + 2 s_1 (s_2 (\alpha^2 + \beta (\beta - \beta_c)) + \beta \beta_c) + s_2^2 (\alpha^2 + (\beta - \beta_c)^2))^{3/2}}$$

$$\partial_{\beta_c} \Delta f^* \text{ Indeterminate}$$

$$\partial_{\beta_c} \Delta f^* = \frac{- \alpha (-1 + s_2) \sqrt{(s_1 + s_2)^2 + (\beta (s_1 + s_2) + (-1 + s_2) \beta_c)}}{(\alpha^2 + \beta^2 s_1^2 + 2 s_2 (\beta - \beta_c) \beta_c + \beta_c^2 + 2 s_1 (s_2 (\alpha^2 + \beta (\beta - \beta_c)) + \beta \beta_c) + s_2^2 (\alpha^2 + (\beta - \beta_c)^2))^{3/2}}$$

When $\beta$ is small relative to $\beta_c$, this derivative can be positive. Otherwise, the derivative is negative.
Firm Profit function, given individual's best response

\[ r_1 (-1 + s_1) - \frac{\alpha^2 (-2 + s_1 + 2 s_2)}{\sqrt{\alpha^2 + \beta^2}} - \sqrt{\frac{\beta^2}{\alpha^2 + \beta^2}} (\beta s_1 + (-1 + s_2) (2 \beta - \beta_c) + (-1 + s_2) \beta_c \frac{\beta_c^2}{\sigma_c^2 + \beta_c^2} + \]

\[ \pi_1 + \pi_2 = \frac{(-1 + s_2) \alpha_c^2 + \beta \sqrt{\frac{(\beta s_1 + s_2 (\beta - \beta_c) + \beta_c)^2}{(\alpha^2 + \beta^2) (s_1 + s_2)^2 - 2 \beta (-1 + s_2) (s_1 + s_2) \beta_c + (-1 + s_2)^2 \beta_c^2}}}{\sqrt{\frac{a^2 (s_1 + s_2)^2}{(\alpha^2 + \beta^2) (s_1 + s_2)^2 - 2 \beta (-1 + s_2) (s_1 + s_2) \beta_c + (-1 + s_2)^2 \beta_c^2}}} \]

Firm Profit graphs for selected parameters and ranges of \( s \) (where \( s_1 = s_2 = s_2 \))

Profit function is well-behaved on \( 0 < s < 1 \), but has a second local optimum at \( s < 0 \).

Firm Profit, \(-1 \times 10^6 < s < 1 \times 10^6\)

- \( a_c = 0.5, \beta_c = 0.1 \)
- \( a_c = 0.9, \beta_c = 0.1 \)
- \( a_c = 0.5, \beta_c = 0.5 \)
- \( a_c = 0.9, \beta_c = 0.5 \)
- \( a_c = 0.5, \beta_c = 0.9 \)
- \( a_c = 0.9, \beta_c = 0.9 \)

\( \alpha = 0.9, \beta = 0.5, r_1 = 0.4 \)
Firm Profit, $-0.5 < s < 1$

\[ \pi_1 + \pi_2 \]

$\alpha = 0.9, \beta = 0.5, r_1 = 0.4$

Firm Profit, $0 < s < 1$

\[ \pi_1 + \pi_2 \]

$\alpha = 0.9, \beta = 0.5, r_1 = 0.4$
APPENDIX B

UNCONSTRAINED MODEL ANALYSIS DETAILS

\[ u_1 = \alpha(\Delta f_1) + \beta(\Delta g_1) \]
\[ u_2 = \alpha(\Delta f_1 + \Delta f_2) + \beta(\Delta g_1 + \Delta g_2) \]
\[ u_2^* = \alpha_c(\Delta f_2) + \beta_c(\Delta g_1 + \Delta g_2) \]

Supplier's problem:

\[
\text{SP} \max_{\Delta f_i, \Delta g_i} \left( (1 - s_1) r_i + s_1 u_i - c(\Delta f_1) - c(\Delta g_1) + (1 - s_2) \max_{\Delta f_i, \Delta g_i} (u_2^* - c(\Delta f_2) - c(\Delta g_2)) + s_2 \max_{\Delta f_i, \Delta g_i} (u_2 - c(\Delta f_2) - c(\Delta g_2)) \right)
\]

\[ \Delta f_2 = \frac{\alpha}{k_f}, \Delta g_2 = \frac{\beta}{k_g} \text{ (when supplier continues working with firm)} \]

\[ \Delta f_1^* = \frac{(s_1 + s_2)\alpha}{k_f}, \Delta g_1^* = \frac{(s_1 + s_2)\beta + (1 - s_2)\beta_c}{k_g} \]

Firm Problem

\[
\text{FP} \max_{s_1, s_2} \left( (1 - s_1)(u_1 - r_i) + (1 - s_2)(u_2 - u_2^*) \right)
\]

Subject to the firm's participation constraint and supplier choices:

\[
\max_s \left( (1 - s_1)(u_1 - r_i) + (1 - s_2)(u_2 - u_2^*) \right) \geq 0
\]

\[ \Delta f_1^* = \frac{(s_1 + s_2)\alpha}{k_f}, \Delta g_1^* = \frac{(s_1 + s_2)\beta + (1 - s_2)\beta_c}{k_g} \]

\[ \Delta f_2 = \frac{\alpha}{k_f}, \Delta g_2 = \frac{\beta}{k_g} \]
\[ \pi_1 + \pi_2 = \frac{1}{k_f k_g} \left( \frac{\alpha^2 k_g - \alpha^2 k_g (s_1 + s_2 - 2)(s_1 + s_2) + k_f^2 k_g (\alpha_e (s_2 - 1) - \alpha^2 s_2)}{+ k_f \left( \beta^2 + k_g (s_1 - 1) - (\beta (s_1 + s_2 - 2) - \beta_e (s_2 - 1)) (\beta (s_1 + s_2) - \beta_e (s_2 - 1)) \right)} \left( -k_f \beta^2 s_2 - \beta_e^2 (s_2 - 1) \right) \right) \]

**First-order conditions**

\[ s_i^* = \frac{2\alpha^2 k_g (1 - s_i) + k_f (k_g r_i + 2\beta (1 - s_i) (\beta - \beta_e))}{2(\beta^2 k_f + \alpha^2 k_g)} \]

\[ s_i^* = \frac{2\alpha^2 k_g (1 - s_i) + k_f k_g (-\alpha^2 + \alpha_e^2) - k_f (\beta - \beta_e) k_g (\beta^2 + \beta_e (\beta + \beta_e) + 2(-\beta + \beta s_i + \beta_e))}{2(\alpha^2 k_g + k_f (\beta - \beta_e)^2)} \]

When \( s_i \) and \( s_2 \) are constrained to be equal, the first-order condition is:

\[ s^* = \frac{4\alpha^2 k_g + k_f (4\beta^2 + k_g (-\beta^2 k_g + r_i) + k_f k_g (-\alpha^2 + \alpha_e^2) - 6\beta \beta_e + (2 + k_g^2) \beta_e^2)}{2(4\alpha^2 k_g + k_f (-2\beta + \beta_e)^2)} \]

**Hessian matrix of firm profit with respect to \( s_1, s_2 \):**

\[
\begin{pmatrix}
-2\beta^2 k_f - 2\alpha^2 k_g & -2\alpha^2 k_g - 2\beta k_f (\beta - \beta_e) \\
\frac{k_f k_g}{k_f} & \frac{k_f k_g}{k_g}
\end{pmatrix}
\]

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Comparative statics for $s_1, s_2$:

$\partial_{s_1} s_1^* = \frac{k_x k_g}{2 (\beta^2 k_x + \alpha^2 k_g)}$

$\partial_{s_2} s_1^*$ Indeterminate

$\partial_{s_2} s_1^* = -\frac{\alpha k_x k_g (k_g r_1 + 2 \beta (-1 + s_2) \beta_c)}{(\beta^2 k_x + \alpha^2 k_g)^2}$

$\partial_{s_2} s_1^* = 0$

$\partial_{s_2} s_1^*$ Indeterminate

$\partial_{s_2} s_1^* = -\frac{k_x (-\alpha^2 k_g (-1 + s_2) \beta_c + \beta k_x (k_g r_1 + \beta (-1 + s_2) \beta_c))}{(\beta^2 k_x + \alpha^2 k_g)^2}$

$\partial_{s_2} s_1^* = \frac{\alpha^2 k_g (k_g r_1 + 2 \beta (-1 + s_2) \beta_c)}{2 (\beta^2 k_x + \alpha^2 k_g)^2}$

$\partial_{s_2} s_1^* = \frac{\beta k_x (\beta k_x r_1 - 2 \alpha^2 (-1 + s_2) \beta_c)}{2 (\beta^2 k_x + \alpha^2 k_g)^2}$

$\partial_{s_2} s_1^* = 0$
\[ \partial_s s^*_2 = \frac{\alpha k_k k_g (k_k k_g \alpha^2_c + k_g^2 (\beta - \beta_c)^2 - (\beta - \beta_c) (2 s_1 \beta_c + k_g^2 (\beta + \beta_c)))}{(\alpha^2 k_g + k_k (\beta - \beta_c)^2)^2} \]

\[ \partial_s s^*_2 = \frac{k_k^2 k_g \alpha_c}{\alpha^2 k_g + k_k (\beta - \beta_c)^2} \]

\[ \partial_\beta s^*_2 = \frac{k_k (k_k^2 k_g (\alpha^2 - \alpha_c^2) (\beta - \beta_c) + k_k (k_g^2 + s_1) (\beta - \beta_c)^2 \beta_c - \alpha^2 k_g (\beta_k^2 + s_1 \beta_c))}{(\alpha^2 k_g + k_k (\beta - \beta_c)^2)^2} \]

\[ \partial_\beta s^*_2 = \frac{-k_k (k_k^2 k_g (\alpha^2 - \alpha_c^2) (\beta - \beta_c) + k_k (k_g^2 + s_1) (\beta - \beta_c)^2 \beta_c + \alpha^2 k_g (s_1 (\beta - 2 \beta_c) - k_k \beta_c))}{(\alpha^2 k_g + k_k (\beta - \beta_c)^2)^2} \]

\[ \partial_\xi s^*_2 = \frac{-k_k (2 \alpha^2 k_k k_g (\alpha^2 - \alpha_c^2) + k_k^2 (\alpha^2 - \alpha_c^2) (\beta - \beta_c)^2 + \alpha^2 (\beta - \beta_c) (2 s_1 \beta_c + k_k^2 (\beta + \beta_c)))}{2 (\alpha^2 k_g + k_k (\beta - \beta_c)^2)^2} \]

\[ \partial_\xi s^*_2 = \frac{k_k (\beta - \beta_c) (k_k^2 (\alpha^2 - \alpha_c^2) (\beta - \beta_c) + 2 k_k k_g (\beta - \beta_c)^2 \beta_c + \alpha^2 (-2 s_1 \beta_c + k_k^2 (\beta + \beta_c)))}{2 (\alpha^2 k_g + k_k (\beta - \beta_c)^2)^2} \]

Develop hypotheses assuming \( s_1 = s_2 = s, k_f = k_g = 1 \).

\[ s^* = r + 3 \alpha^2 + 3 \beta^2 + \alpha^2_c - 6 \beta_\beta + 3 \beta_c^2 \]

\[ \frac{8 \alpha^2 + 8 \beta^2 - 8 \beta_\beta + 2 \beta_c^2}{\alpha^2 + 3 \beta^2} \]

\[ \partial_\beta s^* = \frac{2 \beta (3 (\alpha^2 + \beta^2) + s_1 + \alpha^2_c) + (9 (\alpha^2 + \beta^2) - s_1 - \alpha^2_c) \beta_c - 3 \beta \beta_c^2}{(4 (\alpha^2 + \beta^2) - 4 \beta \beta_c + \beta_c^2)^2} \]

\[ \partial_\beta s^* = \frac{\alpha (-4 (s_1 + \alpha^2_c) + 12 \beta \beta_c - 9 \beta_c^2)}{(4 (\alpha^2 + \beta^2) - 4 \beta \beta_c + \beta_c^2)^2} \]

\[ \partial_\beta s^* = \frac{-6 \alpha^2 \beta_c + (2 \beta - \beta_c) (-2 (s_1 + \alpha^2_c) + 3 \beta \beta_c - 3 \beta_c^2)}{(4 (\alpha^2 + \beta^2) - 4 \beta \beta_c + \beta_c^2)^2} \]
APPENDIX C - PROJECT CHOICE AND LEARNING SURVEY

Massachusetts Institute of Technology
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Project Choice and Learning Study

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ABOUT THIS SURVEY
The goal of this questionnaire is to understand why people are assigned to different kinds of projects, and what the impact of those choices is on the types of capabilities they develop.

TERM DEFINITIONS
Firm-specific skills are those which are currently of use to only one firm in an industry. For example, a semiconductor firm may use a unique packaging material for its products. The skills the firm’s engineers have accumulated in designing and building products using this material would be of initial use only to this firm. Over time, other firms could decide to adopt the technology, and those skills would become general.

General skills are of immediate use to at least two firms in an industry.

ABOUT THE RESEARCH PROJECT
This research explores how firms and suppliers (including employees) jointly build their technological and business capabilities over time. This study primarily considers the execution of projects (e.g. product or process development projects), where the project is a substantial task which has defined goals and a defined time limit. Examples include new process or product development such as the development of a new computer model or a new version of a software program. The goal of the study is to help firms and suppliers design more productive working relationships.

PLEDGE OF CONFIDENTIALITY
This survey is voluntary; omit any questions you are unable or uncomfortable in answering. Please send your response directly to MIT. Your answers are strictly confidential. No one from your company will be able to see individual questionnaires. MIT will aggregate all responses at the company or industry level. All data will be analyzed and presented on a combined basis only.

AVAILABLE ON WEB
If you prefer to fill out this survey on the web, there is a page at http://web.mit.edu/ggparker/www/research/survey401.html
Section 1.0 Project Characterization

Questions in this section are about your current project (or the project you just completed if you are not yet assigned to another project).

1.0a How much choice among projects did you have before starting your current project? (circle your choice)

1 = No choice was assigned to a project 4 = Some choice, but was heavily influenced to choose 7 = Was free to choose Project Choice

1—2—3—4—5—6—7

1.0b Please briefly describe your current project and up to two of the alternatives you might have considered (if any) before joining your current project: (Include projects you considered during the time window prior to joining your current project).

Current Project ____________________________

_________________________________________________________________________

Alternate #1 ____________________________

_________________________________________________________________________

Alternate #2 ____________________________

_________________________________________________________________________

1.1a Was your current project a major departure from your previous project - requiring a lot of new information, or did it mostly build on knowledge you had? (circle your choice)

1 = No new knowledge 7 = A lot of new knowledge Amount of new knowledge required

1—2—3—4—5—6—7

1.1b If you had a choice, is your current project more firm-specific or less firm specific than the alternative(s)? (check one)

Current project is: ______more firm-specific, or ______Less firm specific

1.2 When your current project is complete, how will it affect your learning, and your opportunities inside and outside your firm? (Please mark the box for your choice)

1 = Low Improvement 7 = High Improvement

1 2 3 4 5 6 7

Firm-Specific Learning

High

Low

General Learning

1 2 3 4 5 6 7

High

Opportunities Inside Firm

Low

1 2 3 4 5 6 7

High

Opportunities Outside Firm

1.3a How much of the learning from your current project would be applicable if you moved to another company? (Consider the best alternative company) _____%
1.3b How much of what you have learned (from all of your projects) at your current employer would be applicable if you moved to another company? (Consider the best alternative company to work for). ________%

1.4a How long is your current project expected to last? __________

1.4b How long was the original planned duration of your current project?_________

1.4c Do you expect your current project to be completed on, over, or under budget? _____On budget _____% Under/Over (circle one)

<table>
<thead>
<tr>
<th>1.5a What are the four most important areas of technical expertise required to complete your current project?</th>
<th>1.5b How long does expertise in the areas listed in 1.5a remain relevant?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Examples: Knowledge of internet communication protocols (TCP/IP), knowledge of specific product line architecture, knowledge of C++.</td>
<td>1 = Briefly - expertise gained last year is becoming obsolete.</td>
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<tr>
<td>Area 1</td>
<td>25 = Very long - expertise gained 25 or more years ago is still relevant</td>
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<tr>
<td></td>
<td>1———-2———-3———-5———-10———-15———-25 years</td>
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<td>1———-2———-3———-5———-10———-15———-25 years</td>
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</table>

1.6 Over the life of the project, how many people have been on your project? Min_________ Max_________ Mean_________

1.7 How is your current project team managed?  
_____By function area (functional managers direct all efforts of their individual departments)  
_____By ‘coordinating project manager’ (directing manager gets approval of function heads for all decisions)  
_____By ‘heavyweight project manager’ (directing manager has significant authority to implement decisions)  
_____Other (please explain)______________________________________________

1.8 Degree of specialization: Are you more of a generalist - learning each new technology and able to move between companies at will, or are you more of a specialist, heavily invested in proprietary technology at your firm?  
1 = Complete generalist 7 = Complete specialist  
1———-2———-3———-4———-5———-6———-7

1.9a Did you complete your previous project at your current employer, or a different firm?  
_____Current employer  _____Different firm
1.9b How much learning from your previous project has been applicable to your current project? _____%

1.10 What is your role on your current project? (Check the best fitting description)

______Technical Contributor (make individual technical contributions)

______Technical Leader (make individual technical contributions, also provide guidance to other technical contributors)

______Technical Manager (make few individual technical contributions, oversee individual technical contributors and leaders)

______Non-Technical Manager (make no individual technical contributions, oversee the work of individual technical contributors and leaders)

______Other __________________________ (Please specify)

1.11a Are the technologies in your company’s products in use at many companies in the industry or are they mostly unique to your company?

(circle your choice)

product technology 1 = widely used in industry 7 = mostly unique to company

1—2—3—4—5—6—7

1.11b Are the product designs for your company’s products in use at many companies in the industry or are the designs mostly unique to your company?

(circle your choice)

product designs 1 = widely used in industry 7 = mostly unique to company

1—2—3—4—5—6—7

1.11c Are your company’s production processes in use at many companies in the industry or are these processes mostly unique to your company?

(circle your choice)

production processes 1 = widely used in industry 7 = mostly unique to company

1—2—3—4—5—6—7

Section 2.0 Incentive Characterization

2.0a Does your firm offer these incentives for good performance on your current project?

1 = Incentive not offered 7 = Firm actively uses this incentive

Better choice of next project

Better in-firm promotion opportunities

Stock options

Direct $ tied to project success

High visibility / praise inside firm

Other __________________________ (specify)

1—2—3—4—5—6—7

2.0b How much are you motivated by the following when choosing/working on projects?

1 = No Motivation 7 = High Motivation

Satisfaction in working at current firm

Project improves job options outside firm

Project advances you in your field

Salary (not tied to particular projects)

Amount of general learning from project

Amount of firm-specific learning from project

1—2—3—4—5—6—7
2.1a How much did your salary change -- in % -- between the start-point of your current project and the start point of your last project? Over what time interval?
______ % Salary Change ______ Time interval between project start points

2.1b Are your performance review periods tied to project end points or to a fixed calendar?

Section 3.0 Background information - answers are optional

All information in this survey will be held confidential - please skip questions you don’t want to answer. However, providing an email address can save a data point if follow-up is needed to clarify a response.

3.0 Today’s date____________________

3.1a Email address ____________________

3.1b Your Name ________________

3.1c Your title ______________________

3.2a Time in your current position ______________________

3.2b How long have you worked at this company? ______________

3.2c How long have you worked in this industry? ______________

3.2d At how many firms in this industry have you worked? __________

3.3 How old are you? ______________

3.4a Are you married? ______________

3.4b If you have children, how old are they? ______________

3.4c Your educational background ___________________________

3.6a Do you own a house/condo? ___

3.6b If you were offered a good job in another city, how easily could you move your household?

1 = No Problem 7 = Impossible

1—2—3—4—5—6—7

3.7a, b How hard would it be for you to find another job at your salary:

In your industry? 1—2—3—4—5—6—7

In another industry? 1—2—3—4—5—6—7

Section 4.0 Survey Feedback

4.0 How clear and easy to answer were the questions in this survey?

1 = Mostly Clear 7 = Mostly Ambiguous

1—2—3—4—5—6—7

4.1 Were any questions particularly difficult to answer? If so, which ones?

4.2 The goal of this questionnaire is to understand why people choose different types of projects, and the impact those choices have on the types of capabilities they develop. Did this questionnaire ask the right questions to probe this issue? If not, what should have been asked? How else would you improve the survey? (Continue on back if necessary)

Thank you for your help!
APPENDIX D

EMPIRICAL DATA SET DETAILS

Participant Firm Profiles

Network Hardware
Designs and manufactures network print servers for all major network protocols (Novell, Appletalk, Token Ring, etc.). Print servers allow multiple computers to share single printers efficiently. Two project examples are: (1) "Porting Netware and Bayyan Vikos from Motorola processor to ARM processor." (2) "Developing/debugging firmware for a new hardware platform." [note that developing firmware is a software task].

Projects require hardware and software engineers to complete. Project durations average 6 months.

Satellite Communications Equipment
Designs and manufactures satellite communications modems for civilian and government customers. Project descriptions: (1) "Packaging and finishing prototype real-time SATCOM system software." (2) "Parallel processing and mathematical simulation in emitter simulation." (3) "Testing a communications feature (cannot go into much further detail than that)" [The third project is for military communications equipment].

Key skills are hardware and software engineering with an emphasis on signal communications processing and microwave electronics. Project durations average 12 months.
Network Software

The group sampled develops software for network server management. Two project examples are: (1) "A minor release of a server management product (expected time to complete is 6 months). This followed a major release that took about 20 months to complete." (2) "Project that combines client/server sockets (TCP/IP and SPK), database and threads in C++.”

Key skills are C/C++ programming and knowledge of network protocols (TCP/IP).

Space Hardware

Supplies fuel tanks for rocket booster engines. Two project descriptions are: (1) "Fracture control of cryogenic fuel tankage for use in a reusable unmanned space vehicle." (2) "Properties of aluminum alloy 2090 hardware when fastener holes are incorrectly prepared."

Primary responsibilities are understanding materials science and ensuring quality control in the production process. Respondents report that project durations average 5 years, but have a standard deviation of 7 years – with some projects lasting from 10 to 20 years.

Medical Electronics

Designs and manufactures medical equipment, some for implantation into human beings. Project descriptions: (1) "Embedded software development for a life support medical device." (2) "Medical pump with supporting hardware, supply test capability to production." (3) "Design, construct, and implement test equipment that’s used in the manufacturing of a medical device."
Projects require mechanical engineers, software engineers, and process engineers to ensure quality control. Projects last 2 years on average.

**Government IT Contracts**

Firm provides software tools for military planners, and internet services to government and commercial customers. Project descriptions: (1) "Decision support tools to project fuel demand for the armed services and the Defense Logistics Agency." (2) "Integration of a commercial product with an existing internet service infrastructure."

Respondents describe key skills as "general [internet] security knowledge (types of common vulnerabilities, things to look for, ways to plug the holes)" and "solid programming skills in C, Java, Perl, Lisp, C++." Projects last about a year and a half on average.

**IT consulting**

Employees provide information technology consulting to services -- usually on location at client firms. Project descriptions: (1) "Design for a web-based fund trading application for a leading mutual fund provider in the Bay Area." (2) "Developing a financial payment application."

Key skills are reported to be "Object Oriented Analysis and Design," and "C++ / Visual C++." Project last under 6 months.

**Workstation graphics**

Group at workstation computer firm which develops graphics hardware and software for unix/NT based workstations. Project descriptions: (1) "Develop in-house tool for extracting PCB manufacturing data/re-write in-house tool
from UNIX to NT platform." (2) "A high performance low-cost graphics device. The project has a relatively high research and development component." (3) "NT/Unix Inter-operability - put in place a method to work in an NT/Unix environment."

Key skills are "Signal Integrity Modeling (SPICE and other tools)" [note - SPICE is a hardware device simulation package used in integrated circuit and printed circuit board design], "graphics pipelines," and "knowledge of Unix OS." Projects last roughly a year.

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143
Data transformed to improve normality using Box-Cox power transform:

\[ x(\lambda) = \frac{x^{1-1/\lambda}}{\lambda}, \quad \lambda \neq 0 \]

\[ x(\lambda) = \ln(x), \quad \lambda = 0 \]

\[ \lambda \text{ was chosen to maximize the following function:} \]

\[ \text{Objective function} \]

\[ \text{Data transformed to improve normality using Box-Cox power transform:} \]

\[ x(\lambda) = \frac{x^{1-1/\lambda}}{\lambda}, \quad \lambda \neq 0 \]

\[ x(\lambda) = \ln(x), \quad \lambda = 0 \]

\[ \lambda \text{ was chosen to maximize the following function:} \]

\[ \text{Objective function} \]
\[ l(x, \lambda) = -\frac{n}{2} \ln \left[ \frac{1}{n} \sum_{j=1}^{n} \left( x_j^{(\lambda)} - \overline{x_j^{(\lambda)}} \right)^2 \right] + (\lambda - 1) \sum_{j=1}^{n} \ln x_j \]

Where \( \overline{x_j^{(\lambda)}} = \frac{1}{n} \sum_{j=1}^{n} x_j^{(\lambda)} = \frac{1}{n} \sum_{j=1}^{n} \frac{x_j^\lambda - 1}{\lambda} \)