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Information, Incentives, and Option Value: The Silicon Valley Model[1]

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This paper analyzes the Silicon Valley model as a novel economic institution in the domain of technological product system innovation. We analyze the informational relationship as well as governance relationships between venture capitalists and a cluster of entrepreneurial firms. The informational conditions that make the Silicon Valley model efficient are identified, leading to an understanding of the significance of standardized interfaces, modularization, and information encapsulation. We then examine the governance/incentive aspect by integrating the models of Aoki (*Towards a Comparative Institutional Analysis*, Cambridge, MA: MIT Press, 2001) and Baldwin and Clark (*Design Rules—Vol. 1*: *The Power of Modularity*, Cambridge, MA: MIT Press, 2000). The paper concludes by evaluating the applicability of the model to other localities and industries. *J. Comp. Econ.*, December 2002, **30**(4), pp. 759–786. Department of Economics, Stanford University, Stanford, California 94305, and RIETI, 1-3-1 Kasumigaseki, Chiyoda-ku, Tokyo 100-0013, Japan; and Faculty of Economics, Toyo University, 5-28-20 Hakusan, Bunkyo-ku, Tokyo 112-8606, Japan. © 2002 Association for Comparative Economic Studies. Published by Elsevier Science (USA). All rights reserved.

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1. INTRODUCTION

In the aftermath of the so-called dot.com bubble and crash, the previous enthusiasm for the Silicon Valley phenomenon seems to have faded somewhat. The fact still remains, however, that Silicon Valley has been successful in bringing a lot of outstanding entrepreneurial firms into existence. What mechanism made Silicon Valley a major driving force for product system innovation, especially in the information and communications industry? Can it be transplanted into a wide variety of local and industrial domains beyond Silicon Valley? The purpose of this paper is to analyze the Silicon Valley phenomenon as a novel economic institution in the domain of technological product system innovation.

The most conspicuous example of the Silicon Valley phenomenon can be found in the computer industry. As documented by Baldwin and Clark (2000), the computer industry was virtually a monopoly market dominated by IBM until the early 1970s. A group of entrepreneurial firms, mostly small and funded by venture capitalists, have been set up since the 1970s and have been very agile in R&D activities. The apparent feature common to these entrepreneurial firms is that they usually develop and produce modular parts of a product system, rather than competing with IBM by producing a stand-alone product system. Thus, many new subindustries have been formed within the domain of the traditional computer industry, and a variety of R&D activities traditionally conducted within IBM are now conducted independently. This process has drastically changed the landscape of the computer industry. A new product system is now formed evolutionarily by selecting and combining *ex post* new modular products developed by entrepreneurial firms. In this sense, a novel and unique economic institution has emerged in the domain of product system innovation. Henceforth, we call this system of product system innovation the Silicon Valley Model (Aoki, 2001).

Property rights theory, as developed by Grossman and Hart (1986) and Hart and Moore (1990), might be applied to explain why R&D activities previously conducted within an established integrated firm came to be conducted independently by small entrepreneurial firms. However, this approach cannot easily explain the unique manner of processing information that is prevalent in Silicon Valley. As Saxenian (1994) points out, substantial degrees of information sharing across competing entrepreneurial firms, on the one hand, and information hiding or encapsulation, on the other, are observed in Silicon Valley. Understanding these ostensibly contradictory phenomena is the key to understanding the Silicon Valley model.[2]

Baldwin and Clark (2000) attempt to understand the Silicon Valley model by focusing on how information is processed in the design of a product system.

[2] Rajan and Zingales (1998) attempt to generalize the basic model of the property rights approach. These authors point out that the original property rights models put exclusive emphasis on the ownership of physical assets as a source of power. They assert that power can come from allocation of access to various kinds of critical resources, such as specialized machines, good ideas, and talented people.

They submit that the modular design of a complex system such as a computer is the key to understanding the emergence of a large modular cluster of firms and markets in the computer industry. They also demonstrate how modularization of a product system could create huge value in a short period of time. They regard the value created by R&D activities as real options, because a random outcome of R&D activity in the current period will be adopted if and only if its potential value exceeds the default value embodied in the current product system. They identify several operators enabled by modularization of a product system that can enhance the value resulting from R&D activities. They conclude that having more smaller modules by splitting the whole design, i.e., a splitting operator, is more profitable than having one large system, and that mounting parallel experiments in the same modular component, i.e., a substitution operator, yields more value. While their explanation of the power of modularity is persuasive, they do not explicitly analyze the incentives of those engaged in R&D activities in the Silicon Valley model. We submit that it is not sufficient to analyze the Silicon Valley model only from the information systemic perspective or to consider only governance aspects. We extend Baldwin and Clark's model of a substitution operator by considering explicitly the incentives of each entrepreneur.

The Silicon Valley phenomenon consists of multifaceted interactions between a cluster of entrepreneurial start-up firms, on the one hand, and venture capitalists as well as leading firms in their respective niche markets, on the other. In order to capture properly the essential nature of this model, it is necessary to identify the unique roles played by those actors. The next section presents our modeling background by describing stylized facts about these relationships. It is not sufficient to look only at the property rights relationship between a venture capitalist and a single entrepreneurial firm because the venture capitalists usually have dual roles in their relationships with entrepreneurial firms. Venture capitalists act as mediators of information and are involved in structuring governance. In Section 3, we develop a team-theoretic model to capture the information-processing activities of venture capitalists and entrepreneurial firms in the course of R&D activities. This enables us to compare different R&D organizations and to identify the conditions under which the Silicon Valley model is superior to a traditional R&D organization with large integrated firms. Section 4 formulates the relationship between a venture capitalist and entrepreneurial firms as a tournament game and analyzes the governance role played by venture capitalists. We extend the model in Aoki (2001) by endogenizing the number of entrepreneurial firms competing in the same component product. Our model is a natural extension of the model of Baldwin and Clark (2000), in which the developmental effort level by each entrepreneurial firm is an exogenous variable. Using this integrated model, we show how the effectiveness of the powerful substitution operator in Baldwin and Clark (2000) is limited by incentive considerations. Section 5 concludes the paper by evaluating the applicability of the Silicon Valley model to other localities and industries.

2. STYLIZED FACTS AS THE MODELING BACKGROUND

Venture capital funds do not usually finance an entrepreneurial firm at an early stage of development. Angel investors often fill this need with small amounts of start-up capital. Angel investors are individuals who invest their own wealth in start-ups but are not directly related to the entrepreneur as family or through a prior friendship. A particular type of angel investor, the successful executive who has made his fortune in his own company, has recently become increasingly important in Silicon Valley. However, a close relationship exists between angels and venture capitalists. In this paper, we do not differentiate explicitly among venture capital funds, venture capital companies, and angel investors, but rather we refer to all of them as venture capitalists.

Venture capitalists seek promising investment projects, while potential entrepreneurs with planned projects but insufficient funds seek financing. There are more than 200 venture capital companies in Silicon Valley and experienced venture capitalists are said to receive over 1,000 applications per year. Suppose that a promising match is found. Unless the reputation of an entrepreneur is already known to venture capitalists and the proposed project is judged to be clearly sound and promising, the venture capitalist provides only seed money initially to see if the entrepreneur is capable of initiating the project and possibly extends aid to help the start-up. When a venture capitalist decides to finance a start-up, elaborate financing and employment agreements are drawn up between the venture capitalist and the entrepreneur.

At the time of start-up, the venture capitalist commits only a fraction of the capital needed to complete the project, with the expectation that additional financing will be made stepwise, contingent upon the project proceeding smoothly, although this may not be contractible. Sahlman (1990) calls this process staged capital commitment. Financing by venture capitalists normally takes the form of convertible preferred stocks or subordinate debt with convertible privileges (Kaplan and Strömberg, 2000; Gompers and Lerner, 1996). This means that venture capitalists are paid prior to holders of common stock in the event of project failure and they also retain an exit option, which is exercisable by refusing additional financing at a critical moment when the firm needs an infusion of new funds to survive. However, a typical shareholding agreement allows an entrepreneur to increase his ownership share, normally in common stock, at the expense of investors, if certain performance objectives are met. Fired entrepreneurs forfeit their claims on stock that has not been vested.

Venture capitalists are well represented on the boards of directors of start-up firms. In addition to attending board meetings, leading venture capitalists often visit entrepreneurs *cum* senior managers at the sites of venture-funded firms. They provide a wide range of advice and consulting services to senior management; they help to raise additional funds, review and assist with strategic planning, recruit financial and human resource managers, introduce potential customers and suppliers, and provide public relations and legal specialists. Venture capitalists also exercise active conventional roles in the governance of the start-up firms and often fire the founder–managers when needed.

If a project is successful, the relational financing terminates either with an initial public offering (IPO) or with acquisitions by other firms. Capital gains are distributed between the venture funds and the entrepreneur according to their shares at that time. Before the dot.com bubble, it usually took 5 to 7 years for the start-up firms to go to the IPO market. During the dot.com boom, this period was shortened, especially for e-commerce businesses. Since the technology involved in those businesses was not strikingly innovative, only new business models needed to be developed. For example, basic analytical algorithms of Internet auction sites have long been known in experimental economics. By contrast, in the biotechnology industry where R&D uncertainty is still relatively high, the period needed for the recovery of venture-capital investment returns has not been shortened significantly. After the crash, the period has tended to get longer again in the information and communications industry.

Recently successful start-up firms show the tendency to become targets of acquisition by leading firms in the same market rather than going to IPO markets. Start-up entrepreneurs prefer buy-outs to IPO's, particularly when they have only a single innovative product line (Hellmann, 1998). Those acquiring firms are often themselves grown-up entrepreneurial firms that have been successful in setting standards in their niche markets. Their aim is to acquire successful start-up firms, either to kill off potential sources of challenges to the standards they have set, or to strengthen their market positions further by shortening the period of in-house R&D through acquisition and development (A&D). These firms also seek to establish a monopolistic position in the market by bundling complementary technologies. Hence, these leading firms have exerted great influence over the activities of venture capitalists and entrepreneurial firms. As a whole, this mechanism enables a new technological product system to be formed evolutionarily by combining flexible new modular products *ex post*.

For the above mechanism to work, the standardized interfaces among different modular products must be prescribed and information-processing activities must be encapsulated or hidden within each entrepreneurial firm in the course of developing respective modular products. This unique mechanism of information sharing and hiding is found by Saxenian (1994) to be the key to the innovative nature of Silicon Valley firms. Standardization of interfaces is as much a product of both the architecture defined by dominant firms, especially Cisco Systems and Microsoft in the current era, and the industry standard-setting organizations, such as Semiconductor Equipment and Materials International (SEMI) and the Internet Engineering Task Force (IETF), as it is of coordination by venture capitalists. Similarly, firms such as Sun are competing with products such as Jini and Java to define the interface standards for emerging markets. Even the leading positions of established firms in respective niche markets may not be secure in highly uncertain and competitive technological and market environments. Rather, standards may be formed evolutionarily and modified through the interaction of large and small firms. In this process, venture capitalists play an important role in intermediating necessary information among these actors, especially entrepreneurial firms.

The above discussion indicates that the venture capitalists play a wide range of roles vis-à-vis entrepreneurial firms; these include *ex ante* monitoring, i.e., the screening of proposed projects to cope with the possible adverse selection problem, *ad interim* monitoring, i.e., checking the actual operation of the firms to mitigate possible moral hazard problems, *ex post* monitoring, i.e., the verification of a project result and the decision as to which exit strategy is to be exercised, and mediation of information regarding standardization of interfaces. Of course, these functions are not fulfilled exclusively by a single venture capitalist. *Ex ante* monitoring requires risk-taking entrepreneurial instinct and ability to draw road maps of technological development. *Ad interim* monitoring requires professional engineering competence in specialized fields and management skills. *Ex post* monitoring requires financial expertise. As a consequence, specialization emerges among venture capitalists to meet the different monitoring needs at the different development stages of an entrepreneurial firm. We abstract from such complications in the real world and assume that a single venture capitalist performs all these functions.

During the dot.com bubble, a large number of start-up entrepreneurial firms were set up under this mechanism and many of them have suffered losses or disappeared. These events might lead one to doubt the viability of the Silicon Valley model. However, the model had been effective even before the dot.com bubble; the crash simply led to a return to the previous situation. The cause of the bubble can be attributed to the lack of rational expectation on the side of investors regarding the value to be realized (Baldwin and Clark, 2002). The mechanism as such remains effective for creating value and therefore deserves to be examined.

3. THE INFORMATION-SYSTEMIC ASPECT OF THE SILICON VALLEY MODEL

3.1. Comparative R&D Organizations

Two major roles of venture capitalists are the mediation of information and the formation of a new product system by selecting and combining modular products *ex post*. Thus, it is natural to ask under what conditions such a unique arrangement of R&D activities can be superior to traditional R&D organizations in a large integrated firm. Suppose that a new technological product system is created by combining component products. For example, a laptop computer consists of such component elements as an LC monitor, an MPU, an image-processing LSI, a hard disk drive, an OS, application software, and audio and communication devices. In general, complicated dependencies exist among the design tasks for those component products. Therefore, developing a complex product system requires continual coordination among design tasks for different component products so that they will fit with one another to form a coherent product system.[3] The volume of information exchanged and processed among those design task units can be so huge that any single agent would not be able to marshal the whole process in a centralized manner. Since each human being is boundedly rational in his information-processing activity, we usually form an organization to transcend partially human limitations and to solve the problem by installing a structured information-processing system.

In order to capture the structured information-processing activities inherent in the development of a complex product system, suppose that a generic R&D organization is composed of a development manager, denoted by M, and of two product design teams, denoted by T_i ($i = a$, b). M is engaged in such tasks as development strategy and the allocation of R&D funds, while the product design teams are engaged in the design of component products of an integral technological system. They coordinate their activities to maximize the value of the product system in uncertain environments. The environments are assumed to be segmented as follows. A systemic segment E_s, hereafter systemic environment, may represent the availability of total R&D funds and emergent industrial standards. It affects simultaneously the organizational returns to decisions by M and by the T_i's. In addition, segments of engineering environments affect the organizational returns to the choices by the T_i's. The engineering environments can be divided further into three subsets. E_e, hereafter the systemic engineering environment, is common to both teams and may represent the uncertainty arising in the interface between the T_i's. E_a and E_b, hereafter idiosyncratic engineering environments, are specific to the respective projects of the teams and may represent the technical difficulties particular to the respective tasks.

Assuming that the activities of each member are aligned linearly, the situation can be formulated as a team-theoretic model following Marschak and Radner (1972). Suppose that the value of the technological product system, which is also the payoff common to all the members, is expressed as

$$V(x, y_a, y_b) = \gamma_s x + (\gamma_s + \gamma_e + \gamma_a) y_a + (\gamma_s + \gamma_e + \gamma_b) y_b - \frac{A}{2}x^2 + Dx(y_a + y_b) - \frac{K}{2}(y_a + y_b)^2 - \frac{L}{2}(y_a - y_b)^2, \quad (1)$$

where x is M's choice variable and the y_i's are the choice variables of the T_i's.[4] There are both stochastic parameters and constant parameters in this payoff

[3] A similar argument is found in Baldwin and Clark (2000), who use a design structure matrix (DSM) and a task structure matrix (TSM) to describe dependencies among design parameters and design tasks, respectively.

[4] This payoff function may be thought of as a second-order Taylor series approximation of a general payoff function around the optimal values of x and the y_i's with respect to the prior distribution of the stochastic parameters. We also normalize the payoff so that the expected payoff is zero when there is no *ex post* information other than the priors.

function. The constant parameters are related to technological complementarity among the members' choice variables, i.e., the activity levels, while the stochastic parameters perturb the returns to those activities. Specifically, γ_{s}, γ_{e}, γ_{a}, and γ_{b} are stochastic parameters expressing uncertainty arising in environments $\mathrm{E_s}$, $\mathrm{E_e}$, $\mathrm{E_a}$, and $\mathrm{E_b}$, respectively. Observe that γ_{s} affects the returns to x as well as to the y_i's and γ_{e} affects those to the y_i's, while γ_i affects only y_i. The members can do better by adjusting their activity levels based on the information obtained regarding those stochastic variables. The constant parameters are K, L, A, and D. Note that, because $\partial^2 V/\partial y_{\mathrm{a}} \partial y_{\mathrm{b}} = (L - K)$ measures the degree of technological or design attribute complementarity, the choice variables of the T_i's are complements when $K < L$ and substitutes when $K > L$. It is natural to assume that the choice variables of M and the T_i's are complementary, namely, that $\partial^2 V/\partial x \partial y_i = D > 0$. Under the above assumptions, the sufficient conditions for the value function to be strictly concave in $(x, y_{\mathrm{a}}, y_{\mathrm{b}})$ are $A > 0$, $K + L > 0$, $AK - D^2 > 0$.[5] Without loss of generality, let K and L be positive, because any value of $K + L$ and $K - L$ can be produced by selecting positive K and L appropriately.

In what follows, we assume that M is engaged in observing $\mathrm{E_s}$ and the E_i's are observed only by the T_i's with $i =$ a or b. Specifications about other observations and information, sharing via communication will characterize each type of R&D organization. Since any agent cannot observe all environmental variables, he must base his decision only on partial information, so that we are in a second-best situation. Assume that all the observations of environmental variables are accompanied by some error due to bounded rationality. In this team-theoretic setting, the R&D organization first decides how to share the various kinds of information among the members, although complete information sharing is ruled out. Given such an information structure, the organization then adopts second-best decision rules to maximize the expected payoff. A decision rule maps pieces of available information to choice variables. We are interested in what type of R&D organization is most successful in coordinating agents' choice variables for a specific set of parameters. A type of R&D organization is defined to be informationally more efficient than another if the maximized expected payoff to it is greater than that to the other. Hence, this type of R&D organization is superior to the other as a coordination system for a given set of parameters.

We assume that all environmental shocks are normally distributed with a mean of zero. The errors that accompany the observations of $\mathrm{E_s}$, $\mathrm{E_e}$, $\mathrm{E_a}$, and $\mathrm{E_b}$ are denoted by ε_{s}, ε_{e}, ε_{a}, and ε_{b}, respectively. They are assumed to be independently and normally distributed with a zero mean. Thus, we have

$$\gamma_{\mathrm{s}} \sim N\big(0, \sigma_{\gamma_{\mathrm{s}}}^2\big), \quad \gamma_{\mathrm{e}} \sim N\big(0, \sigma_{\gamma_{\mathrm{e}}}^2\big), \quad \gamma_i \sim N\big(0, \sigma_i^2\big) \quad (i = \mathrm{a, b})$$

[5] In other words, the Hessian matrix is negative definite.

and

$$\varepsilon_{\mathrm{s}} \sim N\left(0, \sigma_{\varepsilon_{\mathrm{s}}}^2\right), \quad \varepsilon_{\mathrm{e}} \sim N\left(0, \sigma_{\varepsilon_{\mathrm{e}}}^2\right), \quad \varepsilon_i \sim N\left(0, \sigma_{\varepsilon_i}^2\right) \quad (i = \mathrm{a}, \mathrm{b}).$$

Other errors either due to the communication process or distinctive to a specific type of organization will be defined when necessary.

In a hierarchical R&D organization, M is the research manager of an integrated firm and the T_i's are internal project teams. Inserted between them is an intermediate agent IM, representing a system engineer. M is specialized in monitoring $\mathrm{E_s}$; we denote M's observation by $\xi_{\mathrm{s}} = \gamma_{\mathrm{s}} + \varepsilon_{\mathrm{s}}$, which is communicated to IM. IM is engaged in monitoring $\mathrm{E_e}$ as well as communicating M's and his observation to the $\mathrm{T_i}$'s. We denote IM's own observation as $\xi_{\mathrm{e}} = \gamma_{\mathrm{e}} + \varepsilon_{\mathrm{e}}$. Thus, the T_i's receive ξ_{s} and ξ_{e} with some communication errors and observe $\xi_i = \gamma_i + \varepsilon_i$. As a result, M's choice variable x depends on ξ_{s}, and the T_i's choice variable y_i depends on $\xi_{\mathrm{s}} + \varepsilon_{\mathrm{s}i}$, $\xi_{\mathrm{e}} + \varepsilon_{\mathrm{e}i}$, and ξ_i, where $\varepsilon_{\mathrm{s}i}$ and $\varepsilon_{\mathrm{e}i}$ denote the communication errors on the side of a T_i. We assume that $\varepsilon_{\mathrm{sa}}, \varepsilon_{\mathrm{sb}} \sim N(0, \sigma_{\mathrm{se}}^2)$, $\varepsilon_{\mathrm{ea}}, \varepsilon_{\mathrm{eb}} \sim N(0, \sigma_{\mathrm{ee}}^2)$ and these errors are all independent. This organization reflects the essential aspects of the R&D organization of a traditional, large hierarchical firm, sometimes referred to as the waterfall model (Klein and Rosenberg, 1986; Aoki and Rosenberg, 1989).

In an interactive R&D organization, M is the research manager and the T_i's are interacting development teams. Information about $\mathrm{E_s}$ is shared among them. The two teams also share information regarding $\mathrm{E_e}$, but they work individually on technical and engineering problems arising in their own segments of the engineering environment E_i. Thus, each project team has wide-ranging information about environments, which is partially shared and partially individual. M's choice variable depends on $\xi_{\mathrm{s}} = \gamma_{\mathrm{s}} + \varepsilon_{\mathrm{s}}$, while the T_i's choices depend on $\xi_{\mathrm{s}} = \gamma_{\mathrm{s}} + \varepsilon_{\mathrm{s}}$, which is common to M and the T_i's, $\xi_{\mathrm{e}} = \gamma_{\mathrm{e}} + \varepsilon_{\mathrm{e}}$, which is common to the T_i's, and $\xi_i = \gamma_i + \varepsilon_i$, which is idiosyncratic to a T_i. This organization corresponds to the chain-linked model of innovation (Klein and Rosenberg, 1986; Aoki and Rosenberg, 1989). Information assimilation is realized both through the feedback of information from the lower level to the higher level and through information sharing and joint development effort across design project teams on the same level.

In a V-mediated information encapsulation organization, information regarding $\mathrm{E_s}$ is shared among M and the T_i's as it is in the interactive R&D organization. However, unlike the interactive R&D organization, there is no information sharing between the T_i's regarding $\mathrm{E_e}$. Thus, development designs are completely encapsulated within each team and their new product design is based on individual, differentiated knowledge. M's choice variable x depends on $\xi_{\mathrm{s}} = \gamma_{\mathrm{s}} + \varepsilon_{\mathrm{s}}$; the choices of the T_i's depend on $\xi_{\mathrm{s}} = \gamma_{\mathrm{s}} + \varepsilon_{\mathrm{s}}$, which is common to M and the T_i's, $\xi_{\mathrm{e}i} = \gamma_{\mathrm{e}} + \varepsilon_{\mathrm{e}i}$, which is idiosyncratic to a T_i, and $\xi_i = \gamma_i + \varepsilon_i$, which is idiosyncratic to a T_i. The same assumption as in the hierarchical R&D organization applies to the $\varepsilon_{\mathrm{e}i}$'s. This internal R&D organization allocates high autonomy in information processing and product design to each project team. However, we regard this model as also capturing some essential aspects of the relationship between venture capitalists and entrepreneurial firms and of the relationships among entrepreneurial firms in Silicon Valley. According to this interpretation, M is a venture capitalist and the T_i's are independent entrepreneurial firms. A substantial degree of information sharing about the emergent industrial systemic environment takes place among them, and venture capitalists often play the role of intermediating such information by mediating contacts among entrepreneurs, engineers, and university researchers.

3.2. Comparative Analysis of Information Efficiency

Since the objective function is quadratic and concave, the second-best decision rule for each agent is linear in pieces of information available to and utilized by him (Marschak and Radner, 1972, Chap. 5). Calculating second-best decision rules yields coefficients that are proportional to the precision of information-processing activity. We adopt the following Bayesian measure of the precision of an observation. Suppose that the prior variance of the observed environmental parameter is σ^2 and the variance of the observation error is σ_z^2; then the precision of the observation is defined as $\Pi = \sigma^2/(\sigma^2 + \sigma_z^2)$. For purposes of comparison, suppose that the above three types of organizations face the same organizational environments, i.e., random variables regarding E_s, E_e, E_i, and all the constant parameters are the same across types. Note that the precision of processing information regarding those environments may vary due to the presence of observation errors. However, if we assume that the precision of processing information is equal across types, tedious calculation establishes the following.

PROPOSITION 1. *Suppose that the three types of R&D organizations face the same stochastic parameters and the same constant parameters and that, for each stochastic parameter, the precision of processing information is the same across organizations. Then the V-mediated information encapsulation organization is informationally more efficient than both the hierarchical and the interactive R&D organization if and only if $K > L$, i.e., when the choice variables of the T_i's are not complementary. Moreover, the interactive R&D organization is informationally more efficient than the hierarchical R&D organization.*[6]

Proof. See the Appendix.

The intuition behind the proposition follows. Since $(L - K)$ measures the degree of technological or design attribute complementarity between the y_i's, an increase in L, which is the coefficient of $(y_a - y_b)^2$, increases the necessity for

[6] This proposition is an extension of a theorem due to Cremer (1990). In the hierarchical R&D organization, communication is one-directional and thus involves communication errors, whereas information is shared completely in the interactive R&D organization. Hence, the interactive R&D organization is informationally more efficient than the hierarchical R&D organization. Considering the cost saved by one-directional communication would change this result. However, we will not be concerned with the comparison between the hierarchical R&D organization and the interactive R&D organization hereafter.

coordinating activity levels between the two tasks, while an increase in K increases the necessity for individual optimization on each task. Thus, the individual information processing in the V-mediated information encapsulation organization becomes more efficient when individual optimization is more important than coordination. In theoretical terms, if the choice variables of design projects are complementary, i.e., the value function is supermodular in the decision variables, it is more profitable to coordinate these variables so that they move in the same direction (Milgrom and Roberts, 1995; Prat, 1996). Such a mechanism is internalized in the hierarchical and interactive R&D organizations because information is more assimilated in those organizations. In contrast, the observations of systemic engineering environments by entrepreneurial firms are mutually hidden in the V-mediated information encapsulation, so that decisions are necessarily less correlated.

In order to focus on the role of technological or design attribute complementarity between the tasks, Proposition 1 examines the case in which the precision of observation is equal across all types of organizations. However, the above description of information-processing activities in each type of organization suggests that the precision of processing information can be different across types. In the interactive R&D organizations, the T_i's are engaged collectively in the observation and communication of $\mathrm{E_e}$, whereas, in the V-mediated information encapsulation organization, $\mathrm{E_e}$ is observed separately and together with E_i. Therefore, suppose that the precision of processing information regarding E_i's is sacrificed relatively more often in the interactive R&D organization because attention is diverted to communications, even though the precision regarding $\mathrm{E_e}$ may be improved due to pooling of data between the agents. Denoting by Π_k^{T} the precision of processing information regarding environment E_k in organization type T, with V designating V-mediated information encapsulation organization and I designating the interactive R&D organization, the above hypothesis is written as $\Pi_i^{\mathrm{V}} > \Pi_i^{\mathrm{I}}$ for $i =$ a or b and $\Pi_{\mathrm{e}}^{\mathrm{I}} > \Pi_{\mathrm{e}}^{\mathrm{V}}$.

If we consider such differences in the precision of processing information across types of organizations, the V-mediated information encapsulation organization can be informationally more efficient than the interactive R&D organization even if $K < L$. The next proposition focuses on the role of statistical correlation between the environments surrounding $\mathrm{T_a}$ and $\mathrm{T_b}$ in determining the relative efficiency of types of organizations when the precision of processing information differs across types.[7]

PROPOSITION 2. *Suppose that the three types of R&D organizations face the same constant parameters. Suppose that* $\Pi_i^{\mathrm{V}} > \Pi_i^{\mathrm{I}}$ *for* $i = a$ *or* b, $\Pi_{\mathrm{e}}^{\mathrm{I}} > \Pi_{\mathrm{e}}^{\mathrm{V}}$, *and* $\Pi_{\mathrm{s}}^{\mathrm{V}} = \Pi_{\mathrm{s}}^{\mathrm{I}}$. *If the systemic segment of the engineering environment is relatively unimportant, i.e.,* $\sigma_{\gamma_{\mathrm{e}}}$ *is small, and the idiosyncratic engineering environment is*

[7] For more detailed comparative statics results in the same framework, see Aoki (2001, Chaps. 4 and 14). As the crux of the present paper is an analysis of the tournament game in the next section, the results in Propositions 1 and 2 are sufficient for our purposes.

relatively important, i.e., σ_i is large, the V-mediated information encapsulation organization is informationally more efficient than the interactive and hierarchical R&D organizations.

Proof. See the Appendix.

The above two propositions are critical to understanding the nature of the unique arrangement of R&D activities in the Silicon Valley model. Baldwin and Clark (2000) note that the concept of modularization of a product system is closely related to the unique informational arrangement of the Silicon Valley model. This concept involves at least three aspects: first, partitioning a product system into relatively independent modules; second, reducing complementarity among the modules through standardization of interfaces among them; and third, a unique mixture of information sharing and information encapsulation. We submit that the third aspect, which is the V-mediated information encapsulation organization, has a close relationship with the first and the second aspects.[8] Furthermore, the second aspect enables the *ex post* formation of a new product system by combining new modular products.

Modularization partitions a complex product system into several modules. A module is a unit of a system within which elements are strongly interrelated to one another, but across which they are relatively independent. To obtain this property of the system, partitioning cannot be carried out arbitrarily. In a different context, Cremer (1980) shows that the optimal way to partition an organization is to minimize the statistical correlations among the units. In the present context, the whole design problem should be divided into two tasks in such a way that statistical correlation between the two is minimized. Hence, the systemic engineering environment for each unit would become relatively unimportant compared with the idiosyncratic engineering environment. As Proposition 2 shows, the V-mediated information encapsulation organization is preferable in such environments. In this sense, good modularization or good architecture of a product system is complementary to the unique informational arrangement observed in Silicon Valley.

All the modules created through this process of partitioning are compatible with one another and work together smoothly. To assure such compatibility, the interfaces among modules must be determined explicitly and clearly. In other words,

[8] Baldwin and Clark (2000) regard modularization-in-design as rationalization in the process of designing a complex product system. When they demonstrate how to modularize a product design by using a Design Structure Matrix, modularization is primarily to contrive an ideal hierarchical information system within the whole design process. Once this is done, or at the same time this is done, other aspects of modularization, such as reduced complementarity between different design tasks and information encapsulation, are supposed to come together immediately. In this sense, our approach is more analytical. We are deriving a second-best organizational arrangement with technological parameters given. Such a difference in the approach may make a somewhat subtle difference between our argument and theirs. According to our analysis, the practice of V-mediated information encapsulation is not realizable if there is indispensable complementarity between project teams or a systemic engineering environment is necessarily very important. Some sorts of product system may not be modularized because of such difficulties.

the interfaces must be standardized. Under well-defined interfaces, R&D activities in the respective modules can be conducted in parallel, which means a reduction in technological complementarity between the two tasks in our model. In general, the choice variables of the T_i's may exhibit some complementarity, so that $K < L$. However, by the standardization of interfaces, K and L become sufficiently close. Thus, standardization of interfaces also makes V-mediated information encapsulation a viable organizational arrangement.

If K is sufficiently close to L, the value function is nearly separable. Hence, improvement of the whole system results from improvement of each modular product, rather than from the coordinated and simultaneous improvement of several modular products. This provides the technological basis for a product system to be formed evolutionarily by combining new modular products. To discuss the *ex post* evolutionary formation of a product system, we must consider the situation in which multiple entrepreneurial firms are present in each module and the standardized interfaces are made open to them publicly. Such a situation will be analyzed in the next section.

The above observation helps us understand why most success stories in Silicon Valley are concentrated in the information and communications industries. The technological development in those industries has been spurred by setting standards for various interfaces arising in the information and communications systems. The modular design of the IBM System/360 is a notable example. Another example can be found in Internet/Web services. The Internet can be seen as a collection of protocols concerning the platform layer, such as TCP/IP and HTML, that are independent of the physical layer. This structure also enables various application software to be developed independently. Once good modular architecture is set, innovations usually take place in individual modules and the architecture and interfaces will change less frequently. In such an environment, complementarity between activities in different modular parts will be reduced and the degree of uncertainty in the systemic segment of the engineering environment will be low. Thus, the V-mediated information encapsulation organization, which we think captures the essence of the Silicon Valley model, will be effective. The next section explores governance in a stylized tournament game to show that it is connected with the information-systemic aspect of the Silicon Valley model analyzed above.

4. THE INCENTIVE ASPECT OF THE SILICON VALLEY MODEL

4.1. Description of the Tournament Game

Assume that time consists of an infinite sequence of stage games. Each stage game is played between venture capitalists and entrepreneurial firms over four dates. The venture capitalists live permanently, competing with one another to nurture valuable firms, while entrepreneurial firms start up at the beginning of date 2 and exit at the end of date 4, either by going public, by being acquired by other firms, or by being terminated. When terminated, an entrepreneur can return to the next stage game as a new candidate for a start-up firm. In the present paper, we do not explore explicitly the repeated nature of the game; rather we concentrate on the analysis of the single stage game between one venture capitalist and multiple start-up firms.[9]

Before providing the details of the stage game, we sketch the whole picture. Suppose that there are only two types of projects. A venture capitalist, henceforth referred to as VC, sets a limit to the number of start-up firms in each project and selects them by screening. Hereafter, we use a start-up firm and its entrepreneur as interchangeable terms. Each of the selected entrepreneurs is engaged in R&D activity that requires effort, which results in the observation of relevant environments. For each type of project, the VC holds a tournament game among entrepreneurs. Once the VC determines winners in the respective tournament games and the VC and the winners choose their activity levels based on their observations of the environments, the value of the whole product system can be written as

$$V(x, y_{\mathrm{a}}, y_{\mathrm{b}}) = \gamma_{\mathrm{s}} x + (\gamma_{\mathrm{s}} + \gamma_{\mathrm{a}}) y_{\mathrm{a}} + (\gamma_{\mathrm{s}} + \gamma_{\mathrm{b}})\, y_{\mathrm{b}} - \frac{A}{2} x^2 + Dx(y_{\mathrm{a}} + y_{\mathrm{b}}) - \frac{K}{2}(y_{\mathrm{a}} + y_{\mathrm{b}})^2 - \frac{L}{2}(y_{\mathrm{a}} - y_{\mathrm{b}})^2, \quad (2)$$

where x is the activity level chosen by the VC and y_i is that chosen by the winner in project type i. As in the previous section, γ_{s} and γ_i are stochastic parameters expressing the uncertainty in the systemic segment $\mathrm{E_s}$ and the idiosyncratic engineering segment E_i of the environment. Unlike in Eq. (1), the systemic engineering environment is not present in Eq. (2), because $\mathrm{E_e}$ is relatively unimportant, i.e., its variance is low, in the Silicon Valley model. Although this value function is similar to that used in the previous section, the analysis in this section takes explicit account of the incentives of the entrepreneurs.

A more detailed description of the stage game follows. At date 1, the VC chooses the number of start-up firms to fund in each project type and screens many R&D projects proposed by cash-constrained would-be entrepreneurs (*ex ante* monitoring). Let the number of selected entrepreneurs in project type i be denoted by n_i. The selected startup firms are indexed by subscripts i and j, where i denotes the project type and $j = 1, \ldots, n_i$ indexes firms in the same project type.

At date 2, each funded start-up firm is engaged in R&D activity that requires effort. The effort level by a start-up firm is denoted by e_{ij} and the associated cost by $c(e_{ij})$, which has the usual property of increasing marginal cost. The R&D effort of the entrepreneur generates noisy one-dimensional information $\xi_{ij,}$ i.e., research results, regarding E_i with precision $\Pi_i(e_{ij})$. We assume that the higher the effort level, the higher is the precision of the entrepreneur's posterior estimates regarding the environment, so that $\Pi_i(e_{ij})$ is increasing. The actual levels of effort

[9] The repeated nature of the game concerns the incentives of venture capitalists. See Aoki (2001, Chap. 14.3) for the impact of repeatedness on venture capitalists' incentives.

exerted by the start-up firms may be inferred, but these are not verifiable in the courts so that they are not contractible. The fixed amount of funds provided to each entrepreneur in project i at this date is denoted by K_i. This amount covers only the cost of processing information at this date and is not sufficient for further product development.

At date 3, communication between the entrepreneurs and the VC occurs. In this process the entrepreneurs and the VC mutually improve and assimilate their estimates of the systemic environment $\mathrm{E_s}$, resulting in assimilated information ξ_s. Suppose that the precision of their assimilated information is an increasing function $\Pi_s(\cdot)$ of the VC's mediating effort level e_{VC}. The costs associated with the VC's mediating and monitoring efforts are represented by $\kappa(e_{VC})$, which has the usual property of increasing marginal costs.

At the beginning of date 4, the VC observes the potential value created by the entrepreneur, but only imprecisely. Based on this observation, the VC estimates which combination of product designs from each type of project is expected to generate higher value, if the respective firms are offered to the public or acquired by an existing firm. According to this estimation, the VC selects one proposal to implement from each type of project and allocates one unit of available funds to the winning entrepreneurs. The start-up firms that are not selected exit.

At the end of date 4, the selected projects are completed. Selected entrepreneurs and the VC make their decisions based upon ξ_{ij} and ξ_s and all environmental uncertainties are resolved. The VC offers the ownership of these firms to the public through markets or sells them to acquiring firms. The realized value V is then distributed among the VC and the entrepreneurs. Suppose that the initial contract is such that, at the time when winners are selected and the value is realized, a fixed share α_i is vested with the winning entrepreneur in project i and the unfunded entrepreneur forfeits any share. Denote the distributive share of the value to the VC by $\alpha_{VC} = 1 - \Sigma_i \alpha_i$. The payoff to the winning firm is then $\alpha_i V - c(e_{ij}) + K_i$ and that to the VC is $\alpha_{VC} V - \kappa(e_{VC}) - \Sigma_i n_i K_i$.

Note that, at date 4, the VC and the entrepreneurs are fully incentivized to choose their activity levels according to the second-best decision rules derived in the previous section. This follows because e_{ij} and e_{VC} have already been exerted at date 2 and date 3, α_{VC} and α_i are fixed, and the expected payoffs to both the winners of the respective projects and to the VC are increasing in V, which does not depend on any effort levels at this juncture.

4.2. Incentive Impacts of Governance by Tournament

At date 4, the VC and the winning entrepreneurs coordinate their decisions according to the second-best decision rules. As was shown in the previous section, the second-best decision rules for the VC and the entrepreneurs are linear in the precision of processing information, $\Pi_s(e_{VC})$ and $\Pi_i(e_{ij})$. Specifically, the second-best decision rule for the VC is $x^* = \frac{D+K}{AK-D^2}\Pi_s(e_{VC})\xi_s$, and that for an entrepreneur is $y_{ij}^{*} = \frac{D+A}{2(AK-D^2)} \Pi_{\mathrm{s}}(e_{\mathrm{VC}})\xi_{\mathrm{s}} + \frac{1}{K+L} \Pi_i(e_{ij})\xi_{ij}$. The resulting expected value if the VC selects entrepreneur j for project a and entrepreneur k for project b is

$$\frac{2D+K+A}{2(AK-D^2)} \sigma_{\gamma_{\mathrm{s}}}^2 \Pi_{\mathrm{s}}(e_{\mathrm{VC}}) + \frac{1}{2(K+L)} \big(\sigma_{\mathrm{a}}^2 \Pi_{\mathrm{a}}(e_{\mathrm{a}j}) + \sigma_{\mathrm{b}}^2 \Pi_{\mathrm{b}}(e_{\mathrm{b}k})\big). \tag{3}$$

Since this expected value is additively separable in the effort levels by the VC and the winning entrepreneurs for both types of projects and the winning entrepreneurs receive a fixed share of the value, the incentive effect on the entrepreneurs is determined by considering only the tournament game within each project.

Since we can restrict our attention to a tournament within a fixed project, henceforth we suppress the subscript i. Suppose that n start-up firms are selected for this project at date 1. Let $e_j \geq 0$ be the effort level exerted by the jth entrepreneur with $j = 1, \ldots, n$, at date 2 and let $c(e_j)$ be its associated cost function. To assure that a unique interior solution exists, we assume that $c(e_j)$ is increasing and convex, that $c'(0) = 0$, and that $c''(\infty) = \infty$. Let the share of the winning entrepreneur in this project type be given by $\alpha \in (0, 1)$. Consider the term in Eq. (3) that is affected by an entrepreneur's effort level. For entrepreneur j engaged in project i, this is $\frac{1}{2(K+L)} \sigma_i^2 \Pi_i(e_{ij})$. Suppressing the subscript i and rewriting σ_i^2 as β, we denote the relevant expected value as $g(e_j, \beta)$, where β represents the degree of uncertainty involved in the R&D activity. Assuming that $\Pi_i(\cdot)$ is differentiable, it follows that $\partial g/\partial e_j > 0$, $\partial g/\partial \beta > 0$, and $\partial^2 g/\partial e_j \partial \beta > 0$.

As an expert in estimating the market values of firms, the VC evaluates the potential market value of each firm with some imprecision and then selects the entrepreneur with the highest value as a winning entrepreneur. Suppose that the VC observes a random variable $y_j = g(e_j, \beta) + \varepsilon_j^{\mathrm{VC}}$ for each j with effort level e_j at the beginning of date 4. Here $\varepsilon_j^{\mathrm{VC}}$ consists of both the VC's observation error with respect to $g(e_j, \beta)$ and the uncertainty in the potential market value of entrepreneurial firm j that is different from, and independent of, the technological uncertainty. We assume that $\varepsilon_j^{\mathrm{VC}} \sim N(0, \sigma_{\mathrm{VC}}^2)$ for all j and that the errors are i.i.d. Thus, a large value of σ^{VC} may result either from low precision of the VC's observation, as measured by $1/\sigma_{\mathrm{VC}}^2$, or from high marketing uncertainty. In what follows, we use either interpretation depending on the context. The resultant expected value created in this project is $\max_j \{g(e_j, \beta) + \varepsilon_j^{\mathrm{VC}}\}$. The winner receives a share α of the realized value and the VC the share α_{VC} once all the technological uncertainty is resolved at the end of date 4.

Suppose that the VC has already chosen $n \geq 2$ entrepreneurs and consider the game at date 2 in which entrepreneurs choose their level of R&D effort. Since each entrepreneur faces the same situation, we restrict our attention to the symmetric Nash equilibrium of this game. Let e^* be the equilibrium level of effort. Then the

jth entrepreneur's problem is described as choosing e_j to maximize

$$\alpha E\Big[\big(g(e_j,\beta)+\varepsilon_j^{\mathrm{VC}}\big)\Pr\Big\{g(e_j,\beta)+\varepsilon_j^{\mathrm{VC}} > g(e^*,\beta)+\max_{k\neq j}\varepsilon_k^{\mathrm{VC}}\Big\}\Big] - c(e_j), \quad (4)$$

where the expectation is taken with respect to $\varepsilon^{\mathrm{VC}} = (\varepsilon_1^{\mathrm{VC}}, \ldots, \varepsilon_n^{\mathrm{VC}})$ and $\max_{k\neq j}\varepsilon_k^{\mathrm{VC}}$ is the maximum order statistic of a sample of size $n-1$ (Galambos, 1984). Denoting the pdf and cdf of $\varepsilon_k^{\mathrm{VC}}$ by f and F, the pdf and cdf of the maximum order statistics of a sample of size $n-1$ are $(n-1)f(x)F(x)^{n-2}$ and $F(x)^{n-1}$, respectively. Rewriting (4) yields

$$\alpha\int_{-\infty}^{\infty}(g(e_j,\beta)+x)F(g(e_j,\beta)-g(e^*,\beta)+x)^{n-1}f(x)\,dx - c(e_j). \quad (5)$$

By differentiating (5) and letting $e_j = e^*$, the symmetric Nash equilibrium condition is

$$\alpha\frac{\partial g(e^*,\beta)}{\partial e_j}\left[\frac{1}{n}+g(e^*,\beta)\int_{-\infty}^{\infty}(n-1)f(x)^2F(x)^{n-2}\,dx + \int_{-\infty}^{\infty}x(n-1)f(x)^2F(x)^{n-2}\,dx\right] = c'(e^*). \quad (6)$$

The first term in the parentheses on the left-hand side is the probability of winning, which turns out to be $1/n$. The second term is the expected payoff times the marginal increase in the probability of winning. The third term is the marginal expected value resulting from the marketing uncertainty. The next proposition is intuitively obvious.

PROPOSITION 3. *Consider the symmetric Nash equilibrium of the subgame in which entrepreneurs choose their effort levels. The equilibrium level of effort is strictly decreasing in the number of selected entrepreneurs for $n \geq 2$, strictly decreasing in the variance of the VC's observation error or the marketing uncertainty, and strictly increasing in the uncertainty involved in R&D activity.*

Proof. For the first and second parts, it suffices to show that the expression enclosed by the brackets on the left-hand side of the Nash equilibrium condition is strictly decreasing in n and σ_{VC}^2 because $c'' > 0$. Suppose $n \geq 2$. By Lemma 2 in the Appendix, the coefficient of the second term is decreasing in n. By Lemma 3 in the Appendix, the sum of the first and the third terms is strictly decreasing in n. Thus, the expression in the brackets on the left-hand side of Eq. (6) is strictly decreasing in n. Denote the pdf and cdf of the standard normal distribution by ϕ and Φ, respectively, so that the coefficient of the second term in the brackets becomes

$$\frac{(n-1)\int_{-\infty}^{\infty}\phi(x)^2\Phi(x)^{n-2}\,dx}{\sigma_{\mathrm{VC}}},$$

which is strictly decreasing in σ_{VC}. The third term can be rewritten as

$$\int_{-\infty}^{\infty} x(n-1)\phi(x)^2\Phi(x)^{n-2}\,dx.$$

Thus, the expression in the brackets on the left-hand side of Eq. (6) is decreasing in σ_{VC}. Finally, observe that the left-hand side of the Nash equilibrium condition is obviously strictly increasing in β. Q.E.D.

Proposition 3 shows that increasing the number of entrepreneurs engaged in the same modular component lowers their incentives to provide effort in the symmetric equilibrium. It also shows that higher precision of the VC's observation or the lower marketing uncertainty along with higher R&D uncertainty induce higher effort levels from the tournament participants. When there is only one entrepreneur in the project, his effort level is determined by $\alpha\frac{\partial g(e,\beta)}{\partial e} = c'(e)$. Keeping the other parameters constant, the tournament elicits higher effort from entrepreneurs if and only if

$$\frac{g(e,\beta)\int_{-\infty}^{\infty}\phi(x)^2\Phi(x)^{n-2}\,dx}{\sigma_{\mathrm{VC}}} + \int_{-\infty}^{\infty} x\phi(x)^2\Phi(x)^{n-2}\,dx > \frac{1}{n}.$$

This inequality holds when σ_{VC} is small and $g(e,\beta)$ is large. Thus, a large prize for the winner, high precision of the VC's monitoring, and a low level of marketing uncertainty are essential for this tournament scheme to work well.

Now we turn to the VC's problem of choosing the optimal number of tournament participants. The expected payoff of the project to the VC when he chooses n entrepreneurs, omitting additional financing cost at date 4, is denoted $\pi_{\mathrm{VC}}(n, \sigma_{\mathrm{VC}}, K)$ and given by

$$\pi_{\mathrm{VC}}(n,\sigma_{\mathrm{VC}},K) = \alpha_{\mathrm{VC}}\left[g(e^*(n,\sigma_{\mathrm{VC}},\beta),\beta) + \int_{-\infty}^{\infty} nxf(x)F(x)^{n-1}\,dx\right] - nK, \tag{7}$$

where e^* is the equilibrium level of effort and K is the cost of start-up financing. Now consider the VC's problem of maximizing (7) over the set of integers with $n \geq 2$. Notice that $g(e^*(n,\sigma_{\mathrm{VC}},\beta),\beta)$ is strictly decreasing in n because Proposition 3 shows that e^* is strictly decreasing in n and $g(\cdot,\beta)$ is strictly increasing in the first argument. The second term in the parentheses is the effect of running n experiments in parallel, which is the expected value of the maximum order statistic of a sample of size n and turns out to be strictly increasing in $n \geq 1$ by Lemma 1 in the Appendix. Thus, we state the next proposition.

PROPOSITION 4. *Consider the VC's problem of maximizing* (7) *over the set of integers with* $n \geq 2$. *The solution set is nonempty. Furthermore, if* $K' < K''$, $n' \in \arg\max_{n:n\in N,n\geq 2} \pi_{\mathrm{VC}}(n, \sigma_{\mathrm{VC}}, K')$ *and* $n'' \in \arg\max_{n:n\in N,n\geq 2} \pi_{\mathrm{VC}}(n, \sigma_{\mathrm{VC}}, K'')$, $n'' \leq n'$.

Proof. Let $W(n) = U(n-1) = \int_{-\infty}^{\infty} nxf(x)F(x)^{n-1}\,dx$. By Lemma 1, $W(n)$ is strictly increasing in n, and $W(n+1)-W(n)$ is strictly decreasing in n. Observe that $\lim_{n\to\infty} W(n) - W(n-1) = 0$. Thus, the maximum of $\alpha_{\mathrm{VC}} W(n) - nK$ is attained. Since $\alpha_{\mathrm{VC}} g(e^*(n, \sigma_{\mathrm{VC}}, \beta), \beta)$ is strictly decreasing in n, the relevant domain for the maximization problem is obviously bounded above and thus finite. This proves the existence of the solution.

It is easy to see that the objective function has strictly increasing differences in $(n, -K)$. By the well-know theorem of monotone comparative statics (Topkis, 1998, p. 79), $K' < K''$, $n' \in \arg\max_{n:n\in N,n\geq 2} \pi_{\mathrm{VC}}(n, \sigma_{\mathrm{VC}}, K')$ and $n'' \in \arg\max_{n:n\in N,n\geq 2} \pi_{\mathrm{VC}}(n, \sigma_{\mathrm{VC}}, K'')$ imply that $n'' \leq n'$. Q.E.D.

Proposition 4 indicates that increasing the number of tournament participants induces increased benefits from parallel experiments but at the cost of decreased incentives for tournament participants. The model developed in this section is regarded as an extension of both the tournament model in Aoki (2001) and the model of the substitution operator in Baldwin and Clark (2000). The former model analyzes the incentives of tournament participants when the number of participants is fixed at two, while the latter model abstracts from the effects of increasing the number of competitors on the entrepreneurs' incentives.[10] These results suggest that incentive considerations can limit the effectiveness of the substitution operator.

We can also derive some interesting implications concerning the dot.com bubble in which most entrepreneurial firms were engaged in e-commerce businesses. Although the dot.com bubble and the ensuing crash may have been caused primarily by erroneous expectations regarding profitability, the number of entrants into Internet/Web services was very large because their start-up costs were low. Proposition 3 suggests that the incentives of the entrepreneurs were affected adversely by such a large number of entrants. The technology involved in those businesses was not strikingly innovative and only new business models were needed. Thus, most e-commerce businesses had low technological uncertainty and high

[10] In Baldwin and Clark (2000), the result of R&D activity in the current period is adopted if it turns out to be superior to the old one, i.e., they regard the result of R&D activities in modular designs as real options. They suggest that the greater is the number of parallel experiments, the greater is the value of real options, which they call the value of substitution. Although our model does not model explicitly the value of the tournament as a real option, the same increasing property can be obtained so that increasing the number of entrepreneurs has the effect of conducting more parallel experiments.

marketing uncertainty, which would also have affected the entrepreneurs' incentives adversely.

5. CONCLUSION

In this paper, we argue that a novel institutional arrangement for product system innovation has emerged in Silicon Valley and try to capture its innovative nature. We consider multifaceted relationships between venture capitalists and a cluster of entrepreneurial firms and focus on both the information structural relationship and the governance relationships. Our analysis of comparative R&D organizations indicates that the application of the Silicon Valley model may be limited to domains in which a product system design can be partitioned into modular products by standardized interfaces, so that the technological complementarity between them is reduced. On the other hand, our analysis of the governance relationship between a venture capitalist and entrepreneurial firms suggests that the Silicon Valley model may be effective when successful developmental projects are expected to yield extremely high values in markets, where there are venture capitalists who are capable of high-quality monitoring, and where marketing uncertainty is low but technological uncertainty is high. We show that an increase in the number of entrants affects the incentives of entrepreneurs adversely and that the optimal number of entrants is decreasing in the amount required for start-up financing.

The identification of conditions for the informational efficiency of information encapsulation may have broader implications for corporate organizations. Because of the development of communications and transportation technology, even mature products such as automobiles are decomposed increasingly into modules. In these modules production and procurement become less integrated than in traditional hierarchical firms, as represented by American firms of a decade ago, or in interactive firms, as represented by Japanese firms. This tendency renders compact modular organizations, either in the form of independent firms or subsidiaries, increasingly more efficient. Various innovations in corporate governance evolving in existing firms appear to emulate the Silicon Valley model. Governing subsidiaries with flexible coupling and decoupling and less operational intervention, but with tournament-like financial discipline, is such an example and will be the subject of another paper.

APPENDIX

We first present the second-best decision rules and the expected payoff for each type of R&D organization. The second-best decision rules are linear in the pieces of information available as shown by Marschak and Radner (1972, p. 168). Hence, say in the case of a hierarchical R&D organization, we can let $x = \lambda_{\mathrm{s}}\xi_{\mathrm{s}}$, $y_i = \lambda_{\mathrm{s}i}(\xi_{\mathrm{s}} + \varepsilon_{\mathrm{s}i}) + \lambda_{\mathrm{e}i}(\xi_{\mathrm{e}} + \varepsilon_{\mathrm{e}i}) + \lambda_i \xi_i (i = \mathrm{a, b})$ and then solve for the coefficients λ_{s}, $\lambda_{\mathrm{s}i}$, $\lambda_{\mathrm{e}i}$, and λ_i that together maximize the expected payoff. This method of derivation is followed for all types of organizations.

A1: Organizational Decision Rules

The Hierarchical R&D Organization

In this case, the second-best decision rules are

$$x = \frac{K + D\Pi_{se}}{AK - D^2\Pi_{se}} \Pi_s^H \xi_s$$

and

$$y_i = \frac{D + A}{2\big(AK/\Pi_{se} - D^2\big)} \Pi_s^H(\xi_s + \varepsilon_{si}) + \frac{1}{2K}\Pi_e^H(\xi_e + \varepsilon_{ei}) + \frac{1}{K+L}\Pi_i^H \xi_i (i = \text{a, b}),$$

where

$$\Pi_s^H = \frac{\sigma_{\gamma_s}^2}{\sigma_{\gamma_s}^2 + \sigma_{\varepsilon_s}^2},$$

$$\Pi_{se} = \frac{\sigma_{\gamma_s}^2 + \sigma_{\varepsilon_s}^2}{\sigma_{\gamma_s}^2 + \sigma_{\varepsilon_s}^2 + \sigma_{se}^2},$$

$$\Pi_e^H = \frac{\sigma_{\gamma_e}^2}{\sigma_{\gamma_e}^2 + \sigma_{\varepsilon_e}^2 + \sigma_{ee}^2},$$

and

$$\Pi_i^H = \frac{\sigma_i^2}{\sigma_i^2 + \sigma_{\varepsilon_i}^2} (i = \text{a, b}).$$

By substitution, the maximized expected payoff is calculated as

$$\frac{2D + K/\Pi_{se} + A}{2(AK/\Pi_{se} - D^2)} \sigma_{\gamma_s}^2 \Pi_s^H + \frac{1}{2K}\sigma_{\gamma_e}^2 \Pi_e^H + \frac{1}{2(K+L)}\big(\sigma_a^2 \Pi_a^H + \sigma_b^2 \Pi_b^H\big).$$

The Interactive R&D Organization

For this case, the second-best decision rules are

$$x = \frac{K + D}{AK - D^2} \Pi_s^I \xi_s$$

and

$$y_i = \frac{D + A}{2(AK - D^2)} \Pi_s^I \xi_s + \frac{1}{2K}\Pi_e^I \xi_e + \frac{1}{K+L}\Pi_i^I \xi_i (i = \text{a, b}),$$

where

$$\Pi_{\mathrm{s}}^{\mathrm{I}} = \frac{\sigma_{\gamma_{\mathrm{s}}}^2}{\sigma_{\gamma_{\mathrm{s}}}^2 + \sigma_{\varepsilon_{\mathrm{s}}}^2},$$

$$\Pi_{\mathrm{e}}^{\mathrm{I}} = \frac{\sigma_{\gamma_{\mathrm{e}}}^2}{\sigma_{\gamma_{\mathrm{e}}}^2 + \sigma_{\varepsilon_{\mathrm{e}}}^2},$$

and

$$\Pi_i^{\mathrm{I}} = \frac{\sigma_i^2}{\sigma_i^2 + \sigma_{\varepsilon_i}^2} (i = \mathrm{a, b}).$$

By substitution, the maximized expected payoff is

$$\frac{2D + K + A}{2(AK - D^2)} \sigma_{\gamma_{\mathrm{s}}}^2 \Pi_{\mathrm{s}}^{\mathrm{I}} + \frac{1}{2K} \sigma_{\gamma_{\mathrm{e}}}^2 \Pi_{\mathrm{e}}^{\mathrm{I}} + \frac{1}{2(K + L)} \left(\sigma_{\mathrm{a}}^2 \Pi_{\mathrm{a}}^{\mathrm{I}} + \sigma_{\mathrm{b}}^2 \Pi_{\mathrm{b}}^{\mathrm{I}}\right).$$

The V-Mediated Information Encapsulation Organization

Here the second-best decision rules are

$$x = \frac{K + D}{AK - D^2} \Pi_{\mathrm{s}}^{\mathrm{V}} \xi_{\mathrm{s}}$$

and

$$y_i = \frac{D + A}{2(AK - D^2)} \Pi_{\mathrm{s}}^{\mathrm{V}} \xi_{\mathrm{s}} + \frac{1}{(K - L)\Pi_{\mathrm{e}}^{\mathrm{V}} + (K + L)} \Pi_{\mathrm{e}}^{\mathrm{V}} \xi_{\mathrm{e}i} + \frac{1}{K + L} \Pi_i^{\mathrm{V}} \xi_i (i = \mathrm{a, b}),$$

where

$$\Pi_{\mathrm{s}}^{\mathrm{V}} = \frac{\sigma_{\gamma_{\mathrm{s}}}^2}{\sigma_{\gamma_{\mathrm{s}}}^2 + \sigma_{\varepsilon_{\mathrm{s}}}^2},$$

$$\Pi_{\mathrm{e}}^{\mathrm{V}} = \frac{\sigma_{\gamma_{\mathrm{e}}}^2}{\sigma_{\gamma_{\mathrm{e}}}^2 + \sigma_{\mathrm{ee}}^2},$$

and

$$\Pi_i^{\mathrm{V}} = \frac{\sigma_i^2}{\sigma_i^2 + \sigma_{\varepsilon_i}^2} (i = \mathrm{a, b}).$$

By substitution, the maximized expected payoff is

$$\frac{2D+K+A}{2(AK-D^2)}\sigma_{\gamma_s}^2\Pi_s^V+\frac{1}{(K-L)\Pi_e^V+(K+L)}\sigma_{\gamma_e}^2\Pi_e^V+\frac{1}{2(K+L)}\left(\sigma_a^2\Pi_a^V+\sigma_b^2\Pi_b^V\right).$$

A2: Proofs of Propositions

Proof of Proposition 1

By assumption, σ_{γ_s}, σ_{γ_e}, $\sigma_i (i = \text{a, b})$ and the constant parameters are all equal across types of R&D organizations and $\Pi_s^H = \Pi_s^I = \Pi_s^V, \Pi_e^H = \Pi_e^I = \Pi_e^V, \Pi_i^H = \Pi_i^I = \Pi_i^V$. First, observe that the only difference in the maximized expected payoff between a hierarchical R&D organization and an interactive organization lies in the coefficient of Π_s^T for $T = \text{H}$ or I. Since $(2D + K + A)/(AK - D^2)$ is decreasing in K and Π_{se} is less than 1, the coefficient in the maximized expected payoff for the hierarchical R&D organization is less than that for the interactive R&D organization. This establishes the second half of the statement of Proposition 1. Now it suffices to make a comparison between the interactive R&D organization and the V-mediated information encapsulation organization.

In this comparison, the only difference lies in the coefficient of Π_e^T for $T = \text{I}$ or V. We have

$$\frac{1}{(K-L)\Pi_e^V+(K+L)} > \frac{1}{2K}$$

if and only if

$$K - L > 0. \qquad \text{Q.E.D.}$$

Proof of Proposition 2

Noting that $\Pi_s^V = \Pi_s^I$, let the maximized expected payoff for the V-mediated information encapsulation organization be greater than that for the interactive R&D organization. Thus, we obtain

$$\frac{1}{2(K+L)}\left[\sigma_a^2\left(\Pi_a^V-\Pi_b^I\right)+\sigma_b^2\left(\Pi_b^V-\Pi_b^I\right)\right] > \sigma_{\gamma_e}^2\left[\frac{\Pi_e^I}{2K}-\frac{\Pi_e^V}{(K-L)\Pi_e^V+(K+L)}\right].$$

Since $\Pi_i^V > \Pi_i^I$ for $i = \text{a}$ or b and $\Pi_e^I > \Pi_e^V$ by hypothesis, the above inequality holds for sufficiently large σ_i 's or sufficiently small σ_{γ_e}. Q.E.D.

A3: Lemmas

In this appendix, $f(x)$ and $F(x)$ denote the generic pdf and cdf of a normal distribution $N(0, \sigma^2)$, respectively.

LEMMA 1. *Let n be a nonnegative integer. The expected value of the maximum order statistic of a sample of size $n+1$, denoted as $U(n)=\int_{-\infty}^{\infty} x(n+1)f(x)F(x)^n\,dx$, is strictly increasing in n. Furthermore $U(n+1)-U(n)$ is strictly decreasing in n.*

Proof. Suppose $n \geq 0$.

$$\begin{aligned}
\frac{U(n+1)}{n+2} &= \int_{-\infty}^{\infty} xf(x)F(x)^{n+1}\,dx \\
&= [(F(x)-1)xF(x)^{n+1}]_{-\infty}^{\infty} - \int_{-\infty}^{\infty}(F(x)-1)(F(x)^{n+1} \\
&\quad + x(n+1)f(x)F(x)^n)\,dx \\
&= \int_{-\infty}^{\infty}(1-F(x))F(x)^{n+1}\,dx + \int_{-\infty}^{\infty}(1-F(x))x(n+1)f(x)F(x)^n\,dx \\
&= \int_{-\infty}^{\infty}(1-F(x))F(x)^{n+1}\,dx + \int_{-\infty}^{\infty} x(n+1)f(x)F(x)^n\,dx \\
&\quad - \int_{-\infty}^{\infty} x(n+1)f(x)F(x)^{n+1}\,dx \\
&= \int_{-\infty}^{\infty}(1-F(x))F(x)^{n+1}\,dx + U(n) - \frac{(n+1)U(n+1)}{n+2}.
\end{aligned}$$

Thus

$$U(n+1)-U(n) = \int_{-\infty}^{\infty}(1-F(x))F(x)^{n+1}\,dx > 0.$$

Therefore, $U(n)$ is strictly increasing in n and $U(n+1)-U(n)$ is strictly decreasing in n. Q.E.D.

LEMMA 2. *Let n be an integer that is greater than or equal to 2 and denote $T(n)=\int_{-\infty}^{\infty}(n-1)f(x)^2F(x)^{n-2}\,dx$. Then, $T(n)$ is decreasing in n for $n \geq 2$ and it is strictly decreasing in n for $n \geq 3$.*

Proof. For $n \geq 2$,

$$\begin{aligned}
\frac{T(n+1)}{n} &= \int_{-\infty}^{\infty} f(x)^2F(x)^{n-1}\,dx \\
&= [(F(x)-1)f(x)F(x)^{n-1}]_{-\infty}^{\infty} - \int_{-\infty}^{\infty}(F(x)-1)(f'(x)F(x)^{n-1} \\
&\quad + (n-1)f(x)^2F(x)^{n-2})\,dx
\end{aligned}$$

$$= \int_{-\infty}^{\infty} (1 - F(x)) f'(x) F(x)^{n-1}\, dx + \int_{-\infty}^{\infty} (1 - F(x))(n-1) \times f(x)^2 F(x)^{n-2}\, dx$$

$$= \int_{-\infty}^{\infty} (1 - F(x)) f'(x) F(x)^{n-1}\, dx + \int_{-\infty}^{\infty} (n-1) f(x)^2 F(x)^{n-2}\, dx - \int_{-\infty}^{\infty} (n-1) f(x)^2 F(x)^{n-1}\, dx$$

$$= \int_{-\infty}^{\infty} (1 - F(x)) f'(x) F(x)^{n-1}\, dx + T(n) - \frac{(n-1)T(n+1)}{n}.$$

Thus

$$\begin{aligned} T(n+1) - T(n) &= \int_{-\infty}^{\infty} (1 - F(x)) f'(x) F(x)\, dx \\ &= \int_{-\infty}^{\infty} f'(x) F(x)^{n-1}\, dx - \int_{-\infty}^{\infty} f'(x) F(x)^n\, dx \\ &= \int_{-\infty}^{\infty} -\frac{x}{\sigma^2} f(x) F(x)^{n-1}\, dx - \int_{-\infty}^{\infty} -\frac{x}{\sigma^2} f(x) F(x)^n\, dx \\ &= \frac{1}{\sigma^2}\left[\int_{-\infty}^{\infty} x f(x) F(x)^n\, dx - \int_{-\infty}^{\infty} x f(x) F(x)^{n-1}\, dx\right] \\ &= \frac{1}{\sigma^2}\left[\frac{U(n)}{n+1} - \frac{U(n-1)}{n}\right] = \frac{1}{\sigma^2}\left[\frac{W(n+1)}{n+1} - \frac{W(n)}{n}\right], \end{aligned}$$

where the third equality follows from $f'(x) = -(x^2/\sigma^2) f(x)$ and $W(n) = U(n-1)$.

Now it suffices to show that $W(3)/3 = W(2)/2$ and that $W(n)/n$ is strictly decreasing in n for $n \geq 3$. For the first part, we have

$$\begin{aligned} \frac{W(2)}{2} - \frac{W(3)}{3} &= \frac{U(1)}{2} - \frac{U(2)}{3} \\ &= \int_{-\infty}^{\infty} x f(x)(1 - F(x)) F(x)\, dx \\ &= \int_{-\infty}^{\infty} x f(x)\left(\frac{1}{4} - G(x)^2\right) dx \\ &= -\int_{-\infty}^{\infty} x f(x) G(x)^2\, dx = 0, \end{aligned}$$

where $G(x) = F(x) - 1/2$ is an odd function and the fifth equality follows because the integrand is also an odd function.

For the second part, the proof proceeds by induction. First, observe that $W(2)/2 = W(3)/3 > W(4)/4$, because $W(4) - W(3) < W(3) - W(2)$. Suppose that $W(2)/2 = W(3)/3 > \cdots > W(k-1)/(k-1) > W(k)/k$, which implies that $W(k) - W(k-1) < W(k)/k$.

$$\begin{aligned}\frac{W(k+1)}{k+1} &= \frac{1}{k+1}(W(k+1) - W(k)) + \frac{k}{k+1}\frac{W(k)}{k} < \frac{1}{k+1}(W(k) - W(k-1)) \\ &\quad + \frac{k}{k+1}\frac{W(k)}{k} < \frac{W(k)}{k},\end{aligned}$$

where the first inequality follows from $W(k+1) - W(k) < W(k) - W(k-1)$ and the second inequality follows from $W(k) - W(k-1) < W(k)/k$. Thus $W(n)/n$ is strictly decreasing in n for $n \geq 3$. Q.E.D.

LEMMA 3. *For $n \geq 2$, let $S(n) = 1/n + \int_{-\infty}^{\infty} x(n-1)f(x)^2 F(x)^{n-2}\,dx$. Then, $S(n)$ is strictly decreasing in n.*

Proof. First, observe that

$$\int_{-\infty}^{\infty} (n-1)f(x)(1 - F(x))F(x)^{n-2}\,dx = \int_0^1 (n-1)(1-y)y^{n-2}\,dy = \frac{1}{n}.$$

By substitution, we have

$$\begin{aligned}S(n) &= \int_{-\infty}^{\infty} (n-1)f(x)(1-F(x))F(x)^{n-2}\,dx + \int_{-\infty}^{\infty} (n-1)xf(x)^2 F(x)^{n-2}\,dx \\ &= (n-1)\int_{-\infty}^{\infty} f(x)(1 - F(x) + xf(x))F(x)^{n-2}\,dx.\end{aligned}$$

For $n \geq 2$, we have

$$\begin{aligned}\frac{S(n+1)}{n} &= \int_{-\infty}^{\infty} f(x)(1 - F(x) + xf(x))F(x)^{n-1}\,dx \\ &= \int_{-\infty}^{\infty} [F(x) - 1]'(1 - F(x) + xf(x))F(x)^{n-1}\,dx \\ &= [(F(x) - 1)(1 - F(x) + xf(x))F(x)^{n-1}]_{-\infty}^{\infty} \\ &\quad - \int_{-\infty}^{\infty} (F(x) - 1)[(n-1)f(x)(1 - F(x) + xf(x))F(x)^{n-2} \\ &\quad + xf'(x)F(x)^{n-1}]\,dx\end{aligned}$$

$$
\begin{aligned}
&= \int_{-\infty}^{\infty} (1 - F(x))(n-1) f(x)(1 - F(x) + x f(x)) F(x)^{n-2}\, dx \\
&\quad + \int_{-\infty}^{\infty} (1 - F(x)) x f'(x) F(x)^{n-1}\, dx \\
&= \int_{-\infty}^{\infty} (n-1) f(x)(1 - F(x) + x f(x)) F(x)^{n-2}\, dx - \int_{-\infty}^{\infty} (n-1) \\
&\quad \times F(x)^{n-1}(1 - F(x) + x f(x)) f(x)\, dx \\
&\quad + \int_{-\infty}^{\infty} (1 - F(x)) x f'(x) F(x)^{n-1}\, dx \\
&= S(n) - \frac{n-1}{n} S(n+1) + \int_{-\infty}^{\infty} (1 - F(x)) x f'(x) F(x)^{n-1}\, dx.
\end{aligned}
$$

Thus

$$
\begin{aligned}
S(n+1) - S(n) &= \int_{-\infty}^{\infty} (1 - F(x)) x f'(x) F(x)^{n-1}\, dx \\
&= -\frac{1}{\sigma^2} \int_{-\infty}^{\infty} (1 - F(x)) x^2 f(x) F(x)^{n-1}\, dx < 0. \quad \text{Q.E.D}
\end{aligned}
$$

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