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**The Origins and
Dynamics of Production
Networks in
Silicon Valley**

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ABSTRACT

Computer systems firms in Silicon Valley are responding to rising costs of product development, shortening product cycles, and rapid technological change by focusing and building long-term partnerships with networks of suppliers, both within and outside of the region. Well-known firms like Hewlett-Packard and Apple Computers and lesser known ones like Silicon Graphics and Pyramid Technology are thus organized to combine the components and sub-systems made by specialist suppliers into new computer systems. As these firms collaborate to both define and manufacture new systems, they are institutionalizing their capacity to learn from one another. Three cases--a contract manufacturer, a silicon foundry, and the joint development of a microprocessor--demonstrate how this process of joint learning helps account for the sustained technological dynamism of the regional economy.

Silicon Valley is synonymous with semiconductors in the public mind. Studies of the region's development have largely focused on the development and the dynamics of the semiconductor industry, and when that industry fell into crisis most observers assumed that the region itself would decline. This association is no longer tenable. By the late 1980s, computer systems firms employed as many workers in Silicon Valley as semiconductor producers, and thousands of firms had emerged in related sectors such as software, disk drives, networking hardware, and contract manufacturing.¹

Silicon Valley's systems firms are now at the hub of emerging production networks in the region, networks which are part cause and part consequence of this process of industrial diversification. Well-known firms like Hewlett-Packard and Apple Computers and lesser known ones like Silicon Graphics and Pyramid Technology are organized to recombine components and sub-systems made by specialist suppliers--both within and outside of the region--into new computer systems. As they collaborate with key suppliers to both define and manufacture new systems, they are institutionalizing their capacity to learn from one another. This process of joint learning in turn helps account for the sustained technological dynamism of the regional economy.

Geographers and planners have documented the emergence of flexible forms of production in regions such as Silicon Valley.² However, they have tended to focus on individual sectors in isolation and to overlook the

¹In November 1989, the region's computer industry (SIC 357) employed 62,000 workers, compared to the semiconductor industry's 68,000 (SIC 367). Moreover, employment in computers is predicted to grow to 74,100 by 1995 while employment in semiconductors falls to 43,200. California Employment Development Department, Annual Planning Information, Santa Clara County, June 1989.

²See, for example, Storper and Scott (1988), Scott (1988), Storper and Walker (1989).

growing importance of inter-industry relationships, the redefinition of linkages between firms and sectors, and their consequences for innovation.

In their study of the US semiconductor industry, for example, Scott and Angel (1987) document the vertical disaggregation of production and the dense concentration of inter-firm transactions in Silicon Valley. Yet they fail to explore the equally important relations between the semiconductor firms and their customers, including computer producers. Moreover, their reliance on a transactions costs framework implies that these linkages are purely market exchanges.

When Florida and Kenney (1989) argue that Silicon Valley's flexibility derives from arms-length exchanges and atomistic fragmentation--and thus provides no match for Japan's highly structured, large-firm-dominated linkages--they too overlook evidence documenting the emergence of collaborative supplier relations among the region's technology firms.³ Moreover, it is difficult to reconcile their bleak predictions with the continued dynamism of the Silicon Valley economy.

Students of business organization, by contrast, have focused on the emergence of network forms of industrial organization--intermediate forms which fall between Williamson's ideal types of market exchange and corporate hierarchy. Powell (1987), Johnston and Lawrence (1988), and Miles and Snow (1986) document how the vertical disaggregation of production and the redefinition of supplier relations between complementary producers provide flexibility and responsiveness which are critical in the current competitive environment.

Such research suggests that a network model is superior to the transactions costs approach for characterizing the organization of production in

³See, for example, Gordon (1987, 1989) and Saxenian (1989a).

technology regions.⁴ However, these authors have failed to explore how network forms of organization foster technological innovation. Dosi (1988) characterizes innovation as a local and cumulative process of solving problems in which tacit knowledge and skills are as important as more discrete forms of information. Gordon (1989) and Gambaradella (1989) both analyze cases in which inter-firm cooperation promotes innovation and efficiency.

The case of the computer systems business in Silicon Valley suggests that production networks foster joint learning and complementary technological advance. This paper begins by describing how the region's systems firms are responding to the rising costs of product development, shortening product cycles, and rapid technological change by remaining highly focused and building collaborative relationships with specialist suppliers. In so doing, they are rejecting the vertically integrated model of computer production which dominated in the postwar period, in which a firm manufactured most of its technically sophisticated components and sub-systems internally.

The paper's second section characterizes the high-trust supplier relations which are emerging from this process and blurring the boundaries between interdependent but autonomous firms. This process both builds on and reinforces a process of industrial localization in Silicon Valley. The final section of the paper presents case materials which illustrate how collaboration promotes complementary innovation between Silicon Valley systems makers and their suppliers. This process of reciprocal technological advance in turn promotes the differentiation of computer systems and applications and the formation of specialist computer companies--thereby sustaining the region's continued dynamism.

⁴See Johanson and Mattson (1987) for a comparison of the network and transaction cost approaches.

CREATING PRODUCTION NETWORKS

Competitive conditions in the computer systems business changed dramatically during the 1970s and 1980s. The cost of bringing new products to market increased at the same time that the pace of new product introductions and technological change accelerated. Hewlett-Packard's Vice President of Corporate Manufacturing, Harold Edmondson, claims that half of the firm's orders in any year now come from products introduced in the preceding three years, and notes that:

"In the past, we had a ten year lead in technology. We could put out a product that was not perfectly worked out, but by the time the competition had caught up, we'd have our product in shape. Today we still have competitive technology, but the margin for catch up is much shorter--often under a year."⁵

Computer makers like HP must now bring products to market faster than ever before, often in a matter of months.

The cost of developing new products has in turn increased along with growing technological complexity. A computer system today consists of the central processing unit (CPU), which includes a microprocessor and logic chips; the operating system and applications software; information storage products (disk drives and memory chips); ways of putting in and getting out information (input-output devices); power supplies; and communications devices or networks to link computers together. Although customers seek to increase performance along each of these dimensions, it is virtually impossible for one firm to produce all of these components, let alone stay at the forefront of each of these diverse and fast-changing technologies.

⁵Interview, Harold Edmondson, Vice President of Corporate Manufacturing, HP, February 5, 1988.

Systems firms in Silicon Valley are thus focusing on what they do best, and acquiring the rest of their inputs from the dense infrastructure of suppliers in the region as well as outside. This represents a fundamental shift from the vertically integrated approach to computer production characterized by IBM and other established US firms. In this model--which survived in an era of slow-changing products and technologies--the firm designed and produced virtually all of the technologically sophisticated components and subsystems of the computer in-house. Subcontractors were used as surge capacity in times of boom demand, and suppliers were treated as subordinate producers of standard inputs.

When Sun Microsystems was established in 1982, by contrast, its founders chose to focus on designing hardware and software for workstations and to limit manufacturing to prototypes, final assembly, and testing. Sun purchases application-specific ICs (ASICs), disk drives, and power supplies, as well as standard memory chips, boxes, keyboards, mice, cables, printers, and monitors from suppliers. Even the CPU at the heart of its workstations is assembled by contract manufacturers.

Why, asks Sun's Vice President of Manufacturing Jim Bean, should Sun vertically integrate when hundreds of specialty shops in Silicon Valley invest heavily in staying at the leading edge in the design and manufacture of microprocessors, disk drives, printed circuit boards (PCBs), and most other computer components and subsystems? Relying on outside suppliers reduces Sun's overhead and insures that the firm's workstations use state-of-the-art technology.

This unbundling also provides the flexibility to introduce new products and rapidly alter the product mix. According to Sun's Bean: "If we were making a stable set of products, I could make a solid case for

vertical integration."⁶ He argues, however, that product cycles are too short and technology is changing too fast to move more manufacturing in-house. Relying on external suppliers allowed Sun to introduce four major new product generations in its first five years of operation, doubling the price-performance ratio each successive year.⁷

The guiding principle for Sun, like most new Silicon Valley systems firms, is to concentrate its expertise and resources on coordinating the design and assembly of a final system, to advance a few critical technologies, and to spread the costs and risks of new product development through partnerships with suppliers. Tandem Computers, for example, manufactures its own printed circuit boards (PCBs), but purchases most other components externally. Mips Computer Systems set out to manufacture the microprocessors and PCBs for its workstations, but quickly sold its chipmaking and board assembly operations in order to focus on system design and development.

The region's more established firms have explicitly recognized their reliance on supplier networks and even fostered their development. Apple Computers' venture capital arm makes minority investments in promising firms which offer complementary technology. In 1984, for example, Apple invested \$2.5 million in Adobe Systems, which produces the laser printer software critical to desktop publishing applications.⁸ Tandem Computers similarly invested in a small local telecommunications company, Integrated Technology

⁶"For flexible, quality manufacturing, don't do it yourself," Electronic Business, March 15, 1987.

⁷And while these workstations were all built with standard components, Sun eludes clone-makers by its sheer pace of new product introduction. By the time a competitor reverse-engineers a Sun product and develops the manufacturing capability to imitate it, Sun has introduced a successive generation which rendered the original product obsolete.

⁸D. Clark, "Apple's Unusual New Venture Capital Arm," San Francisco Chronicle, June 8, 1987.

Inc., and the two firms have jointly developed networking products to link together Tandem non-stop systems.

Firms like Apple, Sun, Tandem, and Mips recognize that the design and production of computers can no longer be accomplished by a single firm: it requires the collaboration of a variety of specialist firms, none of which could complete the task on its own. In the words of Apple's CEO John Sculley (1987), "the lifeblood of the network is the free flow of information and mutual support. Any single entity is only as strong as the other parts make it."

These networks build on the unparalleled agglomeration of engineers and specialist suppliers of materials, equipment, and services in Silicon Valley. This regional infrastructure of skill and technology both supports the continued emergence of new systems producers and allows them to remain specialized. Unbundling reduces entry costs, while the region's social networks foster a continual process of recombination and new firm formation.⁹ This explains the proliferation of new computer firms in Silicon Valley during the 1980s--even as the costs of developing and producing systems skyrocketed.¹⁰

The decentralization of production is not limited to small or new firms seeking to avoid fixed investments. Even Hewlett Packard, which designs and manufacture chips, printed circuit boards, disk drives, printers, tape drives, and many other peripherals and components for its

⁹See Saxenian (1989a) and Angel (1989). One anecdote illustrates how regional social networks support recombination: Silicon Graphics sources its custom central processing unit (CPU) from Mips Computers because the firms' founders were officemates at Stanford. They shared technical visions and plans for many years before actually starting their respective firms. The relationship between the two firms remains extremely close.

¹⁰In 1975, 69 companies produced computer systems in Silicon Valley. By 1980 there were more than 100, and by 1985 the count had risen to 246 companies. It is undoubtedly higher now.

computer systems, has restructured internally to gain flexibility and technical advantage.

During the 1980s, HP consolidated the management of over fifty disparate circuit technology units into two autonomous divisions, Integrated Circuit Fabrication and Printed Circuit Board Fabrication. These cross-cutting divisions now function as internal subcontractors to the company's computer systems and instrument products groups. They have thus gained focus and autonomy, which they lacked as separate units tied directly to product lines. Moreover, they must now compete with external subcontractors for firm business, which has forced them to improve service, technology, and quality. These units are even being encouraged sell to outside customers in some instances. In short, HP appears to be creating a network within the framework of a large firm.

These networks extend beyond the system firms and their immediate suppliers. Silicon Valley's suppliers of electronic components and sub-systems are themselves vertically disaggregated--for the same reasons as their systems customers. Producers of specialty and semicustom ICs, for example, have focused production to spread the costs and risks of chip-making. Some specialize in design, others in process technology, and still others provide fabrication capacity for both chip and systems firms.¹¹

The same is true in disk drives. Innovative producers like Quantum and Maxtor have explicitly avoided vertical integration, relying on outside suppliers not only for semiconductors but also for the thin-film disks, heads, and motors which go into hard drives. Facing the pressures of rapidly changing product designs and technologies, they rely heavily on third-party

¹¹Saxenian (1989b) describes the unbundling of semiconductor production and broader changes in the industry during the 1980s.

sources for most components and perform only the initial design, the final assembly, and testing themselves.

The costs and risks of developing new computer systems products are thus spread across complex networks of autonomous but interdependent firms in Silicon Valley. In an environment which demands rapid new product introductions and continual technological change, no one firm can complete the design and production of an entire computer system on its own. By relying on networks of suppliers--both within the region and more distant--Silicon Valley systems firms gain the flexibility to introduce increasingly sophisticated products faster than ever before.

THE NEW SUPPLIER RELATIONS

Silicon Valley's systems makers are thus becoming increasingly dependent upon their suppliers for the success of their own products. Sun founder Scott McNealy acknowledges that "the quality of our products is embedded in the quality of the products we purchase"--which is no understatement, since so much of a Sun workstation is designed by its suppliers.¹² The highly focused systems producer relies on suppliers not only to deliver reliable products on time but also to continue designing and producing high-quality, state-of-the-art products.

While many systems firms begin as Sun did, integrating standard components from different suppliers and distinguishing their products with proprietary software, virtually all now seek specialized inputs to differentiate their products further. These computer makers are replacing commodity

¹²W. Bluestein, "How Sun Microsystems buys for quality," Electronics Purchasing, March 1988.

semiconductors with ASICs and designing customized disk drives, power supplies, keyboards, and communication devices into their systems.¹³

Competition in computers is thus increasingly based on the identification of new applications and improvements in performance rather than simply lower cost. Silicon Valley firms are well-known for creating new product niches such as Tandem's fail-safe computers for on-line transaction processing, Silicon Graphics' high-performance super workstations with 3D graphics capabilities, and Pyramid Technology's mini-mainframe computer systems. However, even the producers of general-purpose commodity products such as IBM-compatible personal computers ("clones") are being driven to source differentiated components in order to reduce costs or improve the performance of their systems. Everex Systems, for example, designs custom chip sets to improve the performance of its PC clones.¹⁴

The more sophisticated these computers and their components become, the more the systems firms are drawn into long-term partnerships with their suppliers. And as they are increasingly treated as equals in a joint process of designing, developing, and manufacturing innovative systems, the suppliers themselves become innovative and capital-intensive producers of differentiated products.

This marks a radical break with the arms-length relations of traditional mass production, in which suppliers manufactured parts according to standard specifications and competed against one another to lower prices, and in which portions of production were subcontracted as a buffer against

¹³On the trend to customize inputs such as disk drives and power supplies, see R. Faletra and M. Elliot, "Buying in the Microcomputer Market," Electronics Purchasing, October 1988.

¹⁴D. Needle and O. Linderholm, "Everex Reaches for PC Gold," Bay Area Computer Currents, August 23-September 5, 1988.

fluctuations in market demand, output, and labor supply.¹⁵ In this model, suppliers tended to remain subordinate, often dependent on a single big customer. IBM was notorious for managing its suppliers in this fashion until the late 1980s, and Silicon Valley systems firms today explicitly contrast their supplier relations with those of IBM.¹⁶

Silicon Valley systems firms now view relationships with suppliers as long-term investments rather than short-term procurement relationships. They recognize collaboration with suppliers as a way to speed the pace of new product introductions and improve product quality and performance. Most firms designate a group of "privileged" suppliers with whom to build these close relationships. This group normally includes the 20 percent of a firm's suppliers which account for 75-80 percent of the value of its components: typically, 15 to 30 producers of custom ICs, printed circuit boards, disk drives, and other specialized components which are critical to product quality and performance.¹⁷

These relationships are based on shared recognition of the need to insure the success of a final product. Typically, a traditional supplier relationship is transformed by the decision to exchange long-term business plans and share confidential sales forecasts and cost information. Sales forecasts allow suppliers to plan investment levels, while cost information encourages negotiation of prices which guarantee a fair return to the supplier while keeping the systems firm competitive. In some cases, these relationships originate with adoption of Japanese just-in-time (JIT) inven-

¹⁵See Holmes (1986).

¹⁶See McKenna (1989) and E. Richards, "IBM pulls the strings," December 31, 1984, San Jose Mercury News.

¹⁷These numbers were repeated by purchasing managers at several different systems firms.

tory control systems, as JIT focuses joint attention on improving product delivery times and quality. It often requires a reduction in the number of suppliers and the creation of long-term supplier relations as well as the sharing of business plans and technical information.¹⁸

Reciprocity guides relations between Silicon Valley's systems firms and their suppliers. Most of these relationships have moved beyond the inventory control objectives of JIT to encompass a mutual commitment to sustaining a long-term relationship. This requires a commitment not to seek advantage of one another when market conditions change, and can entail supporting suppliers through tough times--by extending credit, providing technical assistance or manpower, or finding new customers.

Businesses commonly acknowledge this mutual dependence. Statements like "our success is their success" or "we want them to feel like part of an extended family" are repeated regularly by purchasing managers in Silicon Valley systems firms (whose roles have fundamentally changed from short-term market intermediaries to long-term relationship-builders during the past decade). Managers describe their relationships with suppliers as involving personal and moral commitments which transcend the expectations of simple business relationships.¹⁹

¹⁸"Special Issue on JIT," Electronics Purchasing, January 1987. When HP introduced JIT in the early 1980s, the firm's dramatic cost reductions and improvements manufacturing efficiency were widely publicized in Silicon Valley. It has since been widely adopted in the region. See "Hewlett-Packard Swears by 'Just-in-Time' System," San Jose Business Journal, June 10, 1985.

¹⁹In the words of Preston Heller, Jr., Chairman of Pioneer-Standard Electronics: "In these partnerships, the relationship transcends just handling an order. There is more than a business relationship involved. In addition to the company's commitment, there are personal commitments by people to make sure things happen. Furthermore, there are moral commitments: not to mislead the other party, to do everything possible to support the other party, and to be understanding." Cited in M. Cohodas, "What makes JIT work," Electronics Purchasing, January 1987.

As a result, suppliers are being drawn into the design and development of new systems and components at a very early stage; and they are typically more closely integrated into the customer's organization in this process. A key supplier is often consulted during the initial phases of a new computer system's conception--between two and five years prior to actual production--and involved throughout the entire design and development process. Some Silicon Valley firms even include suppliers in their design review meetings.

This early cooperation allows the supplier to adapt its products to anticipated market changes and exposes the systems engineers to changing component technologies. In the words of the HP VP for Manufacturing, Harold Edmondson:

"We share our new product aspirations with them and they tell us the technological direction in which they are heading We would never have done it this way 10 years ago."²⁰

Tandem Materials Director John Sims similarly describes how information is shared early in the firm's product development process:

"There is a lot of give and take in all aspects of these relationships We have a mutual interest in each others' survival. We share proprietary product information, and we work jointly to improve designs and develop the latest technologies. We continually push each other to do better."²¹

According to an executive at Silicon Valley contract manufacturer

Flextronics:

"In the early stages of any project, we live with our customers and they live with us. Excellent communication is

²⁰Cited in S. Tierston, "The Changing Face of Purchasing," Electronic Business, March 20, 1989.

²¹Interview, John Sims, Materials Director, Tandem Computers, April 13, 1988.

Once production begins, the relationship between the two firms continues at many different levels. Not only does the customer firm's purchasing staff work with the supplier, but managers, engineers, and production staff at all levels of both firms meet to redefine specifications or to solve technical or manufacturing problems. In many cases, the flow of information between the two firms is continuous.²³

These relationships represents a major departure from the old practice of sending out precise design specifications to multiple sources for competitive bids. In fact, price is rarely considered as important as product quality and reliability in a selecting a key supplier. Most firms choose a reliable, high-quality supplier for a long-term relationship, recognizing that the price will be lower over the long term because unpredictable cost fluctuations will be reduced.

As these relationships mature, it is increasingly difficult to speak of these firms as bounded by their immediate employees and facilities. This blurring of firm boundaries is best illustrated by the case of Adaptec, Inc., a Silicon Valley-based maker of input-output controller devices.²⁴ When it was formed in 1981, Adaptec management chose to focus on product design and development and to rely on subcontractors for both semiconductor

²³The relationship between Flextronics and Sun Microsystems is a good example. Flextronics President Robert Todd meets with Sun's Senior Vice President of Operations for breakfast once a month, to insure that trust is maintained at the top and problems are addressed. Interactions between the two firms at other levels are continuous, involving regular meetings between planning, engineering, and purchasing personnel. As a result, a series of highly personalized relationships have developed between the two firms. Interview, Dennis Stradford, Vice President Marketing, Flextronics, March 3, 1988.

²⁴Input-output devices are electronic components which control the flow of data between computers and storage systems and peripherals. The firm sells VLSI circuits and controller boards which incorporate its circuits and software to both computer and disk drive manufacturers.

fabrication and board assembly. The key to this strategy is the investment Adaptec has made in building long-term partnerships with its key suppliers--including Silicon Valley start-up International Microelectronic Products (IMP), Texas Instruments (TI), and the local division of the contract manufacturer SCI. Adaptec's Vice President of Manufacturing, Jeffrey Miller, describes the high degree of trust which has evolved through continuing interaction between engineers in both organizations, claiming:

"Our relations with our vendors is not much different than my relationship was at Intel with our corporate foundry--except now I get treated as a customer, not as corporate overhead . . . It really is very hard to define where we end and where our subcontractors begin: Adaptec includes a portion of IMP, of TI, and of SCI."²⁵

In the words of the Hewlett Packard Vice President of Manufacturing, the partners in these relationships cooperate in order to "pull one another up relative to the rest of the industry."²⁶ This blurring of the boundaries of the firm transcends distinctions of corporate size or age. While many Silicon Valley start-ups have allied with one another and "grown up" together, others have benefitted from relationships with large established firms, both in and outside of the region.

Moreover, while non-disclosure agreements and contracts are normally signed in these alliances, few believe that they really matter (especially in an environment of high employee turnover like Silicon Valley). Rather, the firms accept that they share a mutual interest in one another's success and that their relationship defies legal enforcement. In short, they recog-

²⁵Interview with Jeffrey Miller, Vice President of Marketing, Adaptec Corporation, May 10, 1988.

²⁶Interview, Harold Edmondson, Vice President of Corporate Manufacturing, HP, February 5, 1988.

nize that the strength of the relationship rests on trust, not on a contract. In the words of Apple's purchasing manager Tom McGeorge:

"We have found you don't always need a formal contract . . . If you develop trust with your suppliers, you don't need armies of attorneys . . . In order for us to be successful in the future, we have to develop better working relationships, better trusting relationships, than just hounding vendors for price decreases on an annual basis."²⁷

Truly collaborative relationships do not, of course, emerge overnight or function flawlessly. It may take years before trust develops or a supplier is given more responsibility. And as with any close relationship, misunderstandings do arise. Some relationships are terminated--or in industry lingo, they result in "divorce"--while others languish temporarily and are revitalized with joint work. What is striking is how many appear to not only survive but to flourish.

Although these relationships are often remarkably close, both parties are careful to preserve their own autonomy. Most Silicon Valley firms will not allow their business to account for more than 20 percent of a supplier's product, and prefer that no customer occupy such a position. Suppliers are thus forced to find outside customers, which insures that the loss of a single account will not put them out of business. This avoidance of dependence protects both supplier and customer, and it promotes the diffusion of technology across firms and industries. One local executive suggests the ideal situation is to hold a preferred position with suppliers, but not an exclusive relationship. "Dependence," he notes, "makes both firms vulnerable."²⁸

²⁷Cited in M. Cohodas, "How Apple buys electronics," Electronics Purchasing, November 1986.

²⁸Interview, Henri Jarrat, President and Chief Operating Officer, VLSI Technology, May 10, 1988.

The new supplier relations have distinct regional consequences. The Materials Director at Apple Computers, Jim Bilodeau, describes the firm's preference for local suppliers:

"Our purchasing strategy is that our vendor base is close to where we're doing business . . . We like them to be next door. If they can't, they need to be able to project an image like they are next door."²⁹

Sun's Materials Director Scott Metcalf similarly claims that:

"In the ideal world, we'd draw a 100 mile radius and have all our suppliers locate plants, or at least supply depots, into the area."³⁰

These managers agree that long-distance communication is inadequate for the continuous and detailed engineering adjustments required in making technically complex electronics products. Face-to-face interaction allows firms to address the unexpected complications in a supplier relationship that could never be covered by a contract. Robert Smith, president of Computer Products/Boschert (CP/B), which makes power supplies for computers and peripherals, explains:

"I don't care how well the specifications are written on paper, they are always subject to misinterpretation. The only way to solve this is to have a customer's engineers right here. There is no good way to do it if you are more than fifty miles away."³¹

²⁹Cited in M. Cohodas, "How Apple Buys Electronics," Electronics Purchasing, November 1986.

³⁰Interview, Scott Metcalf, Director of Materials, Sun Microsystems, March 30, 1988.

³¹In an effort to improve its responsiveness, CP/B recently moved part of its manufacturing from Hong Kong to Silicon Valley. Sun Microsystems, which is now CP/B's neighbor, in turn increased its purchases of the firm's power supplies from \$500,000 to more than \$8 million a year. Interview, Robert Smith, President, CP/B. September 1, 1988.

Nor is this desire for geographic proximity reducible to cost considerations alone. The trust, information exchange, and teamwork which are the basis of collaborative supplier relations require continued interaction which cannot be achieved over long distances.

This is not to suggest that all Silicon Valley systems firms are tightly integrated into cooperative relationships with all of their suppliers. More traditional arms-length relations persist, for example, with suppliers of such commodity inputs as raw materials, process materials, sheet metal, and cables. Tandem Materials Director John Sims similarly notes that, while the specialty chip-makers, contract manufacturers, and disk drive producers have been quick to establish cooperative relations, the commodity semiconductor producers have continued to capitalize on short-term price changes by raising prices during a shortage while seeking collaboration during a glut--thus continually undermining trust and foreclosing opportunities to build long-term relationships.³²

Systems firms in Silicon Valley are, however, redefining their relationships with their most innovative suppliers. A network of long-term, trust-based alliances with innovative suppliers represents a crucial source of advantage for a systems producer. It provides flexibility, which is very difficult for a competitor to replicate, and it provides an framework for ongoing technological exchange and reciprocal innovation.

³²Interview, John Sims, Materials Director, Tandem Computers, April 13, 1988. Even this may be changing, however, as firms like Apple have recently established long-term supply arrangements with US memory chipmakers such as TI in order to avoid price fluctuations or dependence on Japanese producers.

PRODUCTION NETWORKS AND INNOVATION

Silicon Valley is thus far more than an agglomeration of individual technology firms. Its networks of interdependent yet autonomous producers grow and innovate reciprocally. These networks promote new product development by encouraging specialization and allowing firms to spread the costs and risks associated with developing technology-intensive products. They spur the diffusion of new technologies by facilitating information exchange and joint problem-solving between firms and even industries. Finally, the networks foster the application of new technologies because they encourage new firm entry and product experimentation.³³

Three cases demonstrate how these production networks promote technological advance in Silicon Valley. The first is the relationship between systems firms and contract manufacturers, which are changing from sweatshops into technologically sophisticated, capital-intensive businesses as they assume more responsibility for product design and manufacturing. The second case involves the partnership between a large systems firm and a small design specialist--a foundry relationship--in which each contributes distinctive, state-of-the-art expertise to a process of complementary innovation. In the third case, a systems firm spreads the costs of perfecting a state-of-the-art microprocessor through joint product development with a semiconductor producer.

Taken together, these cases demonstrate how collaborative relations encourage joint problem-solving between systems firms and their suppliers and how Silicon Valley's firms are organized to respond collectively to fast-changing markets and technology.

³³For a similar process of network creation in the auto industry, see Sabel, et al. (1989).

Contract manufacturers

Printed circuit board assembly has historically been among the most labor-intensive and least technically sophisticated phases of electronics manufacturing. Contract assembly was traditionally used by systems firms in Silicon Valley to augment in-house manufacturing capacity during periods of peak demand. Commonly referred to as "board stuffing," it was the province of small, undercapitalized, and marginal firms which paid unskilled workers low wages to work at home or in sweatshops. Many of these assemblers moved to low-wage regions of Asia and Latin America during the 1960s and early 1970s.

This profile changed fundamentally during the 1980s.

Systems firms like IBM, HP, Sun, and Apple all expanded their business with local contract manufacturers significantly, in order to lower their fixed costs and respond to shorter product cycles.³⁴ This enabled the region's printed circuit board assemblers to expand and upgrade their technology. As small shops received contracts and assistance from larger systems firms, they invested in state-of-the-art manufacturing automation and assumed more and more responsibility for the design and development of new products.³⁵

Flextronics Inc. was one of Silicon Valley's earliest board-stuffing firms. During the 1970s, it was a small, low-value-added, "rent-a-body" operation which provided quick turnaround PCB assembly for local merchant semicon-

³⁴Industry analysts document how contract manufacturing is growing rapidly in Silicon Valley as systems firms concentrate on designing new products and subcontract manufacturing. They also suggest that contract manufacturing is moving back to the US from low-wage locations in Asia in order to gain faster turnaround and more control over quality. See R. Jones, "Contract manufacturing: coming home to the US," Electronic Business, September 15, 1988.

³⁵While many contract manufacturers fit the model described here, there are still hundreds of small, labor-intensive contract assembly firms in Silicon Valley.

ductor firms. Today it is the largest contract manufacturer in the region, and it offers state-of-the-art engineering services and automated manufacturing.

This transformation began in 1980 when Flextronics was purchased by new management.³⁶ The company has expanded rapidly since then, shifting the bulk of its services from consignment manufacturing, in which the customer provides components which the contract manufacturer assembles according to the customer's designs, to turnkey manufacturing, in which the contract manufacturer selects and procures electronic components as well as assembling and testing the boards.

The shift from consignment to turnkey manufacturing is a shift from a low-risk, low-value-added, low-loyalty subcontracting strategy to a high-risk, high-value-added, high-trust approach, because the contract manufacturer takes responsibility for the quality and functioning of a complete subassembly. This shift greatly increases the systems firm's dependence on its contract manufacturer's process and components. Flextronics' CEO Robert Todd describes the change:

"With turnkey they're putting their product on the line, and it requires a great deal of trust. This kind of relationship takes years to develop and a major investment of people time."³⁷

Todd claims that whereas a consignment relationship can be replicated in weeks, it can take years to build the trust required for a mature turnkey relationship in which the design details of a new product are shared. These

³⁶Robert Todd, the current president and CEO of Flextronics, led this move. Todd was formerly a partner at a local high-technology consulting firm. Through his consulting work, he had observed the decentralization of production in Silicon Valley and perceived an opportunity for an increasingly sophisticated, high-value-added contract manufacturer. Interview, Robert Todd, February 2, 1988.

³⁷Interview, Robert Todd, February 2, 1988.

relationships demand extensive organizational interaction and a surprising amount of integration.³⁸ Not surprisingly, firms which consign their manufacturing typically have six or seven suppliers which compete on the basis of cost, while those relying on turnkey contractors build close relations with only one or two firms, selected primarily for quality and responsiveness.

The shift to turnkey manufacturing has clear consequences for location. Flextronics CEO Robert Todd claims:

"We've never been successful for any length of time outside of a local area. We might get a contract initially, but the relationship erodes without constant interaction. Sophisticated customers know that you must be close because these relationships can't be built over long distances."³⁹

Not surprisingly, the US contract manufacturing business is highly regionalized. Flextronics has created business units and production centers in New England, the Southeast, Southern California, and Hong Kong. SCI Systems, the largest US contract manufacturer, is based in Alabama, where costs are very low, but has a major facility in high-cost Silicon Valley in order to build the relationships needed to serve the local market.

Today over eighty-five percent of Flextronics' business is turnkey; in 1980 it was entirely consignment. This growth was initially due to their close relationship with rapidly expanding Sun Microsystems. Sun now accounts for 24 percent of Flextronics business, and the two firms have explicitly limited this share in order to avoid dependency. Flextronics has worked to diversify its customer base and to spread its risk across business cycles by

³⁸Flextronics Vice President of Marketing Dennis Stradford describes continuous technical and administrative communication between engineers, purchasers, planners, and marketers at Flextronics and the customer. This means lots of meetings--both formal and informal--at all levels of the two organizations, and involves immense amount of sharing. Interview, Dennis Stradford, Vice President of Marketing, Flextronics, March 3, 1988.

³⁹Interview, Robert Todd, CEO, Flextronics, Inc. February 2, 1988.

developing customers in a wide range of different industries. The firm now also serves firms in the disk drive, tape drive, printer, and medical instruments industries.

Two recent trends in contract manufacturing illustrate how specialization breeds technological advance and increasing interdependence. On one hand, Silicon Valley systems companies are relying on contract manufacturers for the earliest phases of board design. Flextronics now offers engineering services and takes responsibility for the initial design and layout of Sun's circuit boards as well as the pre-screening of electronic components. The use of contract manufacturers for board design implies a radical extension of inter-firm collaboration, because systems firms must trust subcontractors with the proprietary designs which are the essence of their products. When successful, such a relationship increases the agility of the systems firm while enhancing the capabilities of the contract manufacturers. In fact, Flextronics is now capable of manufacturing complete systems, although this accounts for only 5 percent of their business.

The second trend, the increasing use of surface-mount technology (SMT), is transforming printed circuit board assembly into a capital-intensive business. While the traditional through-hole assembly technique involves soldering individual leads from an integrated circuit through the holes in circuit boards, SMT uses epoxy to glue electronic components onto the board. The new process is attractive because it produces smaller boards (components can be mounted on both sides of the board) and because it is cheaper in volume than through-hole.

SMT is, however, far more complex and expensive than through-hole assembly. It requires tight design rules, high densities, and a soldering process which demands expertise in applied physics and chemistry and takes

years of experience to perfect. Industry analysts describe SMT as 5-10 times more difficult a process than through-hole. Moreover a single high-speed SMT production line costs more than \$1 million.

Contract manufacturer Solelectron Corporation has led Silicon Valley in the adoption of SMT, investing more than \$18 million in SMT equipment since 1984.⁴⁰ It has captured the business of IBM, Apple, Xerox, and HP (as well as many other smaller Silicon Valley firms) by automating and emphasizing customer service, high quality, and fast turnaround. According to venture capitalist and industry veteran Bill Davidow, Solelectron's manufacturing quality is superior to that found in any systems firm in Silicon Valley.⁴¹

This manufacturing excellence is due in part to Solelectron's investment in state-of-the-art equipment. It is also the result of their expertise accumulated by applying lessons learned from one customer to the next. All of Solelectron's customers thus benefit from learning that would formerly have been captured by individual firms. Moreover, lessons learned in manufacturing for firms in one sector are spread to customers in other sectors, stimulating the inter-industry diffusion of innovations.

The use of contract manufacturers, initially an attempt to spread risks, focus resources, and reduce fixed costs in an era of accelerating new product introductions, is thus producing mutually beneficial technological advance. Contract manufacturers are no longer subordinate or peripheral units in a hierarchical production system. Rather, they have transformed themselves into sophisticated specialists which contribute as equals to the vitality of Silicon Valley's production networks.

⁴⁰G. Lasnier, "Solelectron to acquire 10 advanced surface mount systems," San Jose Business Journal, February 8, 1988.

⁴¹Interview, William Davidow, Partner, Mohr Davidow Ventures, April 21, 1988.

Silicon Foundries

Silicon foundries are the manufacturing facilities used for the fabrication of silicon chips, or semiconductors. The use of external foundries grew rapidly in the 1980s as semiconductor and systems firms began designing integrated circuits themselves but sought to avoid the cost of the capital-intensive fabrication process.⁴² Like contract manufacturers, foundries offer their customers the cumulative experience and expertise of specialists. Unlike contract assemblers, however, silicon foundries have always been technologically sophisticated and highly capital-intensive--and they have thus interacted with customers as relative equals offering complementary strengths. This relationship can be an exchange of services with limited technical interchange, or it can offer significant opportunities for reciprocal innovation.⁴³

The collaboration between Hewlett-Packard and semiconductor design specialist Weitek illustrates the potential for complementary innovation in a foundry relationship. Weitek, which has no manufacturing capacity of its own, is the leading designer of ultra-high-speed "number crunching" chips for complex engineering problems. In order to improve the performance of the Weitek chips, HP opened up its state-of-the-art 1.2 micron wafer fabrication facility, historically closed to outside firms, to Weitek for use as a foundry.

⁴²Saxenian (1989b) describes how Silicon Valley firms are unbundling IC production to spread risks and costs in an increasingly costly, technologically complex, and fast-paced industry.

⁴³There is always some technical interchange between a silicon foundry and its customers because of the need to adjust design specifications to a particular manufacturing process. Thus, the foundry relationship is never simply an arms-length market relationship. There are, however, greater and lesser degrees of interdependence.

This alliance grew out of a problem that HP engineers were having with the development of a new-model workstation. They wanted to use Weitek designs for this new product, but Weitek (which had supplied chip-sets to HP for several years) could not produce chips which were fast enough to meet HP's needs. Realizing that the manufacturing process at the foundry Weitek used slowed the chips down, the HP engineers suggested fully optimizing the Weitek designs by manufacturing them with HP's more advanced fabrication process.

This culminated in a three-year agreement which allows the two firms to benefit directly from each other's technical expertise. The agreement guarantees that HP will manufacture and purchase at least \$10 million worth of the Weitek chip sets in its foundry, and it provides Weitek the option to purchase an additional \$20 million of the chips sets from the foundry to sell to outside customers.

This arrangement assures HP of a steady supply of Weitek's sophisticated chips and allows them to introduce their new workstation faster than if they designed a chip in-house; and it provides Weitek a market and the legitimacy of a close association with HP, as well as guaranteed space in a state-of-the-art foundry. Moreover, the final product itself represents a significant advance over what either firm could have produced independently.

Both firms see the real payoff from this alliance in expected future technology exchanges. According to an HP program manager who helped negotiate the deal: "We wanted to form a long-term contact (sic) with Weitek--to set a framework in place for a succession of business opportunities."⁴⁴ By building a long-term relationship, the firms are creating an alliance which

⁴⁴Cited in S. Jones, "Hewlett-Packard inks major chip deal," San Jose Business Journal, May 18, 1987.

allows each to draw on the other's distinctive and complementary expertise to devise novel solutions to common problems. HP now has greater access to Weitek's design talent and can influence the direction of these designs. Weitek has first-hand access to the needs and future plans of a key customer, as well as assured access to HP's manufacturing capabilities. Both are now better positioned to respond to an unpredictable and fast-changing market.

In spite of this increased interdependence, HP and Weitek have preserved their autonomy. Weitek sells the chip sets they produce on HP's fab to third parties, including many HP competitors, and continues to build partnerships and collect input from its many other customers (in fact, Weitek deliberately limits each of its customers to less than 10 percent of its business). Meanwhile, HP is considering opening its foundry to other outside chip design firms, and it still maintains its own in-house design team. The openness of such a partnership insures that design and manufacturing innovations which grow out of collaboration diffuse rapidly.

Both firms see this relationship as a model for the future. While HP does not intend to become a dedicated foundry, it is looking for other partnerships to allow it to leverage its manufacturing technology using external design expertise. Weitek in turn depends upon a strategy of alliances with firms which can provide manufacturing capacity as well as insights into fast-evolving systems markets.

Collaborative Product Development

Joint product development represents the ultimate extension of interdependence in a networked system. The collaboration between Sun Microsystems and Cypress Semiconductor to develop a sophisticated version of Sun's RISC

microprocessor is a classic example. A RISC chip uses a simplified circuit design that increases computing speed and performance of a microprocessor.⁴⁵

Sun's first workstations were based entirely on standard parts and components. The firm's advantage lay in proprietary software and its ability to introduce new products quickly. Over time, the firm began to distinguish its products by adding new capabilities, enhancing its software, and purchasing semi-custom components. Sun's most significant innovation was to design its own microprocessor to replace the standard Motorola microprocessors used in its early workstations. This RISC-based microprocessor, called Sparc, radically improved the speed and performance of Sun's products--and simultaneously destabilized the microprocessor market.

Sun has further broken with industry tradition by freely licensing the Sparc design, in contrast with Intel and Motorola's proprietary approach to their microprocessors. The firm has established partnerships with five semiconductor manufacturers, which each use their own process technology to produce specialized versions of Sparc. The resulting chips share a common design and software, but differ in speed and price.⁴⁶ After supplying Sun, these suppliers are free to manufacture and market their versions of Sparc to other systems producers.

Sun has thus extended acceptance of its pioneering architecture while recovering some of its development costs and avoiding the expense of producing and marketing the new chip. Its suppliers, in turn, gain a

⁴⁵RISC is the acronym for reduced instruction set computing. While IBM pioneered RISC chips, systems start-ups like Sun and Mips Computers, not semiconductor firms, were the first to commercially produce RISC microprocessors.

⁴⁶The firms are Fujitsu Ltd. (first to manufacture the Sparc chip because the leading US semiconductor firms refused to accept external designs), LSI Logic, Bipolar Integrated Technologies, Cypress Semiconductor, and Texas Instruments.

guaranteed customer in Sun and a new and promising product--which they are jointly promoting.⁴⁷

Collaboration thus allowed Sun to significantly reduce the cost of producing a new microprocessor. The firm spent only \$25 million developing the Sparc chip, compared to Intel's \$100 million investment in its 80386 microprocessor. In the words of one computer executive:

"The real significance of Sparc and of RISC technology is that you no longer have to be a huge semiconductor company, with \$100 million to spare for research and development, to come up with a state-of-the-art microprocessor."⁴⁸

Mips Computer Systems has similarly designed its own RISC chip and licensed it to three Silicon Valley semiconductor vendors.

Sun's partnership with 1983 startup Cypress Semiconductor extends such collaboration the furthest. In 1986 the two firms agreed to jointly develop a high-speed, high-performance version of Sparc. A team of approximately thirty engineers from both companies worked at a common site for a year--thus combining Sun's Sparc architecture and knowledge of systems design and software with Cypress's IC design expertise and advanced CMOS fabrication process. This core team was supported through constant feedback from the product development, marketing, and testing specialists in each firm.

Cypress Vice President of Marketing Lowell Turriff describes the collaboration as an "ideal marriage" characterized by "an amazing environment

⁴⁷Sun's suppliers have created the Sparc Vendor Council, an independent organization dedicated to maintaining technical standards and promote the Sparc microprocessor. This group, which is expected to become an independent company, works collectively on both software development and advertising for Sparc.

⁴⁸B. Schlender, "Computer maker aims to transform industry and become a giant," The Wall Street Journal, March 18, 1988.

of cooperation."⁴⁹ The two firms benefit from complementary expertise: Sun gained access to Cypress's advanced design capabilities and its state-of-the-art CMOS manufacturing facility to produce a very-high-speed microprocessor; Cypress gained an alliance with a rapidly growing systems firm, insights into the direction of workstation technology and a new, high-performance product. Cypress executives envision similar partnerships with customers in other industrial markets, including telecommunications and automobiles.

By building a network of collaborative relationships with suppliers like Cypress, Sun not only reduces the cost and shares the risk of developing its workstations, but it is also able to bring new products with innovative features and architectures to market rapidly. Moreover, since Sun has rejected proprietary systems technologies, only these relationships prevent competitors from imitating Sun's--and this turns out to represent a formidable competitive barrier.

This explains Sun's championing of systems which rely on readily available components and industry standard technologies (or "open standards"). Under this approach, computers made by different firms adhere to industry standards which allow them to use the same software and exchange information with one another. This marks a radical break from the proprietary systems approach of industry leaders IBM, DEC, and Apple. Open standards encourage new firm entry and promote experimentation because they force firms to differentiate their products while remaining within a common industry standard. Proprietary systems, by contrast, exclude new entrants and promote closed networks and stable competitive arrangements.

⁴⁹Interview, Lowell Turriff, Vice President Marketing, Cypress Semiconductor, March 7, 1988.

As Silicon Valley systems producers continue to introduce specialized machines for a growing diversity of applications and users, they are fragmenting computer markets. The market no longer consists simply of mainframes, minicomputers, and personal computers: it is segmented into distinct markets for super-computers, super mini-computers, mini-mainframe computers, engineering workstations, networked mini-computers, personal computers, parallel and multiprocessor computers, and specialized educational computers.⁵⁰ As long as this process of product differentiation promises to continue to undermine mass markets for computers, Silicon Valley's specialist systems producers and their suppliers will continue to flourish.⁵¹

CONCLUSIONS

Technical expertise in Silicon Valley today is spread across hundreds of specialist firms which are increasingly linked in network relationships which foster complementary innovation. Local systems firms and their suppliers are motivated to develop independent technological capabilities while simultaneously learning from one another. These network relationships provide the industry and the region with the flexibility to respond rapidly to changing markets and technologies, while simultaneously insuring that innovation diffuses between firms and across sectors.

We thus find the continued resilience of regional economies such as Silicon Valley, in spite of advances in telecommunications and transportation technology which render firms increasingly footloose.⁵² This is not to suggest that all or even most of a firm's transactions occur within the

⁵⁰"Chipping Away", Financial World, September 30, 1986, and McKenna (1988).

⁵¹McKenna (1989) documents this fragmentation of computer markets. Even the personal computer market is increasingly fragmented among scores of small producers.

⁵²See Sabel (1988) and Schoenberger (1989).

region. Nor is it to claim that the region is or could be economically self-contained. Silicon Valley firms rely heavily on global markets and on distant as well as local suppliers. In fact, one of the region's vulnerabilities is a reliance of some local firms on offshore manufacturing capacity.⁵³

There is, however, a clear trend for Silicon Valley systems firms to prefer local suppliers and to build the sort of collaborative relationships which flourish only with proximity. As these collaborative relations breed complementary innovation and cross-fertilization, the advantages of the region over other locations will continue to multiply.

⁵³Typically it is high-volume, standardized products which are sourced offshore, while more sophisticated, high-value-added production remains in the region. However, the danger of losing critical manufacturing skills and knowhow is real.

This does not mean that Silicon Valley is losing all of its manufacturing. There still is significant amount of manufacturing activity in the region: not only do Apple, Tandem, IBM, and HP continue to manufacture locally, but DEC and Unisys have recently ramped-up major manufacturing operations in the valley.

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