

The origins and dynamics of production networks in Silicon Valley *

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Computer systems firms in Silicon Valley are responding to rising costs of product development, shorter product cycles and rapid technological change by focusing and building partnerships with 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 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 micro-processor – illustrate how inter-firm networks help account for the sustained technological dynamism of the regional economy.

This essay analyzes the origins and dynamics of production networks in Silicon Valley from the perspective of the region's computer systems firms. Students of Silicon Valley have focused almost exclusively on the evolution of the semiconductor industry; when that industry fell into crisis in the mid-1980s, most assumed that the region itself would decline. Yet by the end of the decade, the regional economy had rebounded, as hundreds of new computer producers and suppliers of micro-processors, specialty chips, software, disk drives, networking hardware and other components generated a renewed wave of growth.

This revitalization is evident in regional output and employment figures. In spite of the worst recession in the region's history during 1985–86, the shipments of Silicon Valley high technology manufacturers and software enterprises grew 60 percent between 1982 and 1987 (from \$15 billion

to \$24 billion), and employment in these firms expanded more than 45 percent during the decade. While there were only 69 establishments in the region producing computers in 1975, by 1980 there were 113, and by 1985 the number had more than doubled to 246.¹

These new computer systems firms are at the hub of Silicon Valley's expanding production networks. Well-known companies such as Tandem and Apple Computers, and lesser known ones such as 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 define and manufacture new systems, they are reducing product development times and institutionalizing their capacity to learn from one another. These production networks help account for the sustained technological dynamism of the Silicon Valley economy.

Geographers and other social scientists have documented the emergence of flexible systems of production in regions such as Silicon Valley [22,28,32,2,31]. Most of the research on these regions, however, overlooks the changing nature of inter-firm and inter-industry relationships. In their detailed study of the location of the U.S. semiconductor industry, for example, Scott and Angel document the vertical disaggregation of produc-

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¹ High technology manufacturing and services include: computers and office equipment (SIC 357), communications equipment (SIC 366), electronic components (SIC 367), guided missiles (367), instruments (SIC 38), and data processing (SIC 737). Data on the value of shipments is from the U.S. Census of Manufactures and Census of Service Industries; employment figures are from the California Employment Development Department, ES202 Series; and the number of establishments is from U.S. Bureau of the Census, County Business Patterns.

tion and the dense concentration of inter-firm transactions in Silicon Valley, but do not explore the nature of the relations between semiconductor firms and their customers and suppliers.

When Florida and Kenney 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 growing evidence of the redefinition of supplier relations among U.S. technology firms [8,17]. 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. In the two decades since Richardson [26] observed the pervasive role of cooperation in economic relations, the literature on inter-firm networks and alliances has burgeoned [23,20,16,10,14,15,29]. Nonetheless, there has been little attention to the emergence of inter-firm networks in America's high technology regions.

The case of the computer systems business in Silicon Valley demonstrates how inter-firm networks spread the costs and risks of developing new technologies and foster reciprocal innovation among specialist firms. This paper begins by describing how the region's systems firms are responding to the rising costs of product development, shorter product cycles and rapid technological change by remaining highly focused and relying on networks of 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 analyzes the redefinition of supplier relations among Silicon Valley computer firms and their vendors. The creation of long-term, trust-based partnerships is blurring the boundaries between interdependent but autonomous firms in the region. While this formalization of inter-firm collaboration is recent, it builds on the longstanding traditions of informal information exchange, inter-firm mobility and networking which distinguish Silicon Valley [1,3,27].

The final section of the paper presents three cases which illustrate how inter-firm collaboration fosters joint problem-solving between Silicon Valley systems firms and their specialist suppliers. These cases – of a contract manufacturer, a silicon foundry and the joint development of a micro-processor – demonstrate how the process of complementary innovation helps to account for Silicon Valley's technological dynamism.

This paper draws on the findings of more than 50 in-depth interviews with executives and managers in Silicon Valley-based computer systems firms and suppliers during 1988, 1989 and 1990. The sample includes the region's leading computer systems firms, many computer firms started during the 1980s, and a wide range of producers of semiconductors, disk drives, and other components.

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.²

² Interview, Harold Edmondson, Vice-President of Corporate Manufacturing, Hewlett-Packard Corporation, 5 February 1988.

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.

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, DEC and other established U.S. computer firms.³ In this model, which survived in an era of slower changing products and technologies, the firm designed and produced virtually all of the technologically sophisticated components and sub-systems of the computer in-house. Sub-contractors 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 integrated circuits (ASICs), disk drives, and power supplies as well as standard memory chips, boxes, keyboards, mice, cables, printers and monitors from suppliers. Even the printed circuit board 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 sub-systems? 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."⁴ 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. Sun eludes clone-makers by the sheer pace of new product introduction.

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 critical technologies which represent the firm's core capabilities [24], and to spread the costs and risks of new product development through partnerships with suppliers. Tandem Computers manufactures its own PCBs, but purchases all 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.

Some of the region's firms explicitly recognize their reliance on supplier networks and foster 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. Tandem Computers similarly invested in a small local telecommunications company, Integrated Technology Inc, and the two firms have

³ IBM was forced to rely on outside vendors to an unprecedented extent in the early 1980s in order to bring a personal computer to market rapidly enough to compete with Apple.

⁴ Cited in: "For flexible, quality manufacturing, don't do it yourself," *Electronic Business*, 15 March 1987. In 1990, Sun introduced limited printed circuit board assembly operations, however the firm remains committed to a highly focused strategy.

jointly developed networking products to link together Tandem non-stop systems.

Companies like 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 variety of specialist firms, none of which could complete the task on its own. This reliance on outsourcing is reflected in the high level of sales per employee of Silicon Valley firms: compare Apple's \$369,593 and Silicon Graphics \$230,000 per employee to IBM's \$139,250 and DEC's \$84,972 [25].

These highly focused producers depend on the unparalleled agglomeration of engineers and specialist suppliers of materials, equipment and services in Silicon Valley, and on the region's culture of open information exchange and inter-firm mobility, which foster continual recombination and new firm formation [1,3,27]. This infrastructure supports the continued emergence of new producers, while allowing them to remain specialized, and helps explain the proliferation of new computer systems producers in the region during the 1980s – even as the costs of developing and producing systems skyrocketed.

The decentralization of production and reliance on networks 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 computer systems, has restructured internally to gain flexibility and technical advantage.

During the 1980s, HP consolidated the management of over 50 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 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 to sell to outside customers in some instances. In short, HP appears to be creating a network within the framework of a large firm.

The 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 semi-custom integrated circuits, for example, have focused production to spread the costs and risks of chipmaking. Some specialize in design, others in process technology, and still others provide fabrication capacity for both chip and systems firms [30].

The same is true in disk drives. Innovative producers like Conner Peripherals and Quantum 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 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 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 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.⁵ The highly focused systems producer relies on suppliers not only to deliver reliable products on time but also to continue designing

⁵ Cited in W. Bluestein, “How Sun Microsystems buys for quality,” *Electronics Purchasing*, March 1988.

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 semiconductors with ASICs and designing customized disk drives, power supplies, keyboards and communication devices into their systems.⁶ As specialist suppliers continue to advance technologies critical to their own products, they reproduce the technological instabilities that allow this decentralized system to flourish. And there is little evidence that the pace of innovation in computers will stabilize in the near future.

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 3-D graphics capabilities, and Pyramid Technology's mini-mainframe computer systems. Nonetheless, 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.

The more specialized these computers and their components become, the more the systems firms are drawn into 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 a mass production system, in which suppliers manufactured parts according to standard specifications and competed against one

another to lower price, and in which portions of production were subcontracted as a buffer against fluctuations in market demand, output and labor supply [12]. In this model, suppliers remained subordinate and often dependent on a single big customer. IBM was notorious for managing its suppliers in this fashion during the early 1980s, and Silicon Valley systems firms today explicitly contrast their supplier relations with those of IBM [19].⁷

Silicon Valley systems firms now view relationships with suppliers more as long-term investments than short-term procurement relationships.⁸ 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 that account for 75–80 percent of the value of its components: typically between 15 and 30 producers of integrated circuits, printed circuit boards, disk drives, power supplies, and other components which are critical to product quality and performance.

These relationships are based on shared recognition of the need to insure the success of a final product. Traditional supplier relations are typically transformed by a 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 that 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) inventory 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

⁷ See, for example, E. Richards, "IBM pulls the strings", *San Jose Mercury News*, 31 December 1984.

⁸ D. Davis, "Making the Most of Your Vendor Relationships", *Electronic Business*, 10 July 1989. Collaborative supplier relations have been documented in a wide range of industries, including the US and German auto industries [11,28], the French machine tool industry [18], and the Japanese electronics and auto industries [7,21].

⁶ On 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.

as the sharing of business plans and technical information.⁹

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 take 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 helping them find 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 changed during the past decade from short-term market intermediaries to long-term relationship-builders. Managers describe their relationships with suppliers as involving personal and moral commitments which transcend the expectations of simple business relationships. In the words of one CEO:

In these partnerships, the relationship transcends 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.¹⁰

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 design and development process. Some Silicon Valley firms even include suppliers in their design review meetings.

This early cooperation allows a supplier to adapt its products to anticipated market changes and exposes the systems engineers to changing component technologies. In the words of HP Manufacturing VP 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.¹¹

Tandem's 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.¹²

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 needed between design engineers, marketing people, and the production people, which is Flextronics.¹³

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

⁹ When HP introduced JIT in the early 1980s, for example, the firm's cost reductions and improvements in manufacturing efficiency were widely publicized in Silicon Valley. JIT has since been widely adopted in the region. See “Hewlett-Packard swears by ‘Just-in-Time’ System”, *San Jose Business Journal*, 10 June 1985.

¹⁰ Cited in M. Cohodas, “What makes JIT work”, *Electronics Purchasing*, January 1987.

¹¹ Cited in S. Tierston, “The Changing Face of Purchasing,” *Electronic Business*, 20 March 1989.

¹² Interview, John Sims, Director of Materials, Tandem Computers, 13 April 1988.

¹³ Cited in *The San Jose Mercury News*, 25 July 1988.

cases, the flow of information between the two firms is continuous.

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 well illustrated by the case of Adaptec, Inc., a Silicon Valley based maker of input-output controller devices. When it was formed in 1981, Adaptec management chose to focus on product design and development and to rely on subcontractors for both semiconductor fabrication and board assembly. The key to this strategy is the investment Adaptec has made in building long-term partnerships with its core suppliers – including Silicon Valley start-up International Microelectronic Products (IMP), Texas Instruments (TI), and the local division of the large 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.¹⁴

In the words of HP's Edmondson, the partners in these relationships cooperate in order to "pull one another up relative to the rest of the industry."¹⁵ This blurring of the boundaries of the firm tran-

sends 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. According to Apple Computers' Manager of Purchasing, 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.¹⁶

Of course, truly collaborative relationships do not emerge overnight or function flawlessly. There is a constant tension between cooperation and control. It may take years before trust develops or a supplier is given more responsibility. As with any close relationship, misunderstandings arise. Some relationships are terminated – in industry lingo, they result in "divorce" – while others languish temporarily and are revitalized with joint work. What is striking is how many of these relationships 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

¹⁴ Interview with Jeffrey Miller, Vice-President of Marketing, Adaptec Corporation, 10 May 1988.

¹⁵ Interview, Harold Edmondson, Vice-President of Corporate Manufacturing, HP, 5 February 1988.

¹⁶ Cited in M. Cohodas, "How Apple buys electronics," *Electronics Purchasing*, November 1986.

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."¹⁷

Regional proximity facilitates collaborative supplier relations. 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.¹⁸

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.¹⁹

These managers agree that long-distance communication is often 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. The president of a firm which manufactures 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.²⁰

¹⁷ Interview, Henri Jarrat, President and Chief Operating Officer, VLSI Technology, 10 May 1988.

¹⁸ Cited in M. Cohodas, "How Apple Buys Electronics," *Electronics Purchasing*, November 1986.

¹⁹ Interview, Scott Metcalf, Director of Materials, Sun Microsystems, 30 March 1988.

²⁰ In order to improve its responsiveness, the firm recently moved part of its manufacturing from Hong Kong to Silicon Valley. Sun Microsystems, which is its 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, Computer Products/Boschert, 1 September 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 is difficult to achieve 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. Traditional arms-length relations persist, for example, with suppliers of such commodity inputs as raw materials, process materials, sheet metal, and cables. Nor is it to imply that all of a firm's key suppliers are located in the same region. Many Silicon Valley firms purchase components such as commodity chips or disk drives from Japanese vendors.

Systems firms in Silicon Valley are, however, redefining their relationships with their most important suppliers. A network of long-term, trust-based alliances with innovative suppliers represents a source of advantage for a systems producer which is very difficult for a competitor to replicate. Such a network provides both flexibility and a framework for joint learning and technological exchange.

Production networks and innovation

Silicon Valley today is far more than an agglomeration of individual technology firms. Its networks of interdependent yet autonomous producers are increasingly organized to 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.

Three cases demonstrate how these production networks promote technological advance in Silicon Valley. The first is the relationship of systems firms to their contract manufacturers, which are changing from sweatshops into technologically sophisticated, capital-intensive businesses as they assume more responsibility for product design and

process innovation. The second case involves a foundry relationship between a large systems firm and a small design specialist 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 collaboration fosters joint problem solving and how Silicon Valley's firms are learning to respond collectively to fast changing markets and technology.

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 and Apple expanded their business with local contract manufacturers in order to lower their fixed costs and respond to shorter product cycles. This enabled the region's PCB 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.

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 board assembly for local merchant semiconductor firms. By the late 1980s it was the largest contract manufacturer in the region and offered state-of-the-art engineering services and automated manufacturing.

This transformation began in 1980 when Flextronics was purchased by new management. The company expanded rapidly in the subsequent years, 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.²¹

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 relationships demand extensive organizational interaction and a surprising amount of integration.²² As a result, 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,

²¹ Interview, Robert Todd, CEO, Flextronics Inc., 2 February 1988.

²² Flextronics' CEO meets with Sun's Senior Vice-President of Operations for breakfast once a month to insure that trust is maintained at the top and high-level problems are addressed. Meanwhile planning, engineering, purchasing and marketing personnel from the two firms meet still more frequently – often weekly, and in some cases daily – to solve problems and plan for the future. This involves an immense amount of sharing and typically results in highly personalized relationships between the two firms. Interview, Dennis Stradford, Vice-President of Marketing, Flextronics, 3 March 1988.

selected primarily for quality and responsiveness.

The shift to turnkey manufacturing has clear implications for a firm's 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.²³

This explains why the US contract manufacturing business is highly regionalized. During the 1980s, Flextronics established production facilities in Massachusetts, South Carolina, Southern California, Hong Kong, Taiwan, Singapore, and the People's Republic of China.²⁴ 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.

By 1988 over 85 percent of Flextronics' business was turnkey; in 1980 it had been entirely consignment. This growth was initially due to a close relationship with rapidly expanding Sun Microsystems which by 1988 accounted for 24 percent of Flextronics business. The two firms have explicitly sought to limit this share in order to avoid dependency. Flextronics has diversified its customer base by 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 to 10 times more difficult a process than through-hole. Moreover, a single high speed SMT production line costs more than \$1 million.

Contract manufacturer Solecron Corporation has led Silicon Valley in the adoption of SMT, investing more than \$18 million in SMT equipment since 1984.²⁵ It has captured the business of IBM, Apple, and HP (as well as many smaller Silicon Valley firms) by automating and emphasizing customer service, high quality, and fast turnaround. According to one venture capitalist and industry veteran, Solecron's manufacturing qual-

²³ Interview, Robert Todd, CEO, Flextronics, Inc., 2 February 1988.

²⁴ This expansion was too rapid. In 1989, Flextronics was forced to restructure its worldwide business because of significant excess manufacturing capacity and operating losses which began with a downturn in the disk drive business. To eliminate excess capacity, the production facilities in Massachusetts, South Carolina, Southern California, and Taiwan were sold or closed.

²⁵ G. Lasnier, "Solecron to acquire 10 advanced Surface Mount Systems," *San Jose Business Journal*, 8 February 1988.

ity is superior to that found in any systems firm in Silicon Valley.²⁶

This manufacturing excellence is due in part to Solectron'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 Solectron'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. While many of Silicon Valley's contract assemblers remain small and labor intensive, some, such as Flextronics and Solectron, 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 the region's production networks.

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 [30]. 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.

The collaboration between Hewlett-Packard and semiconductor design specialist Weitek il-

lustrates 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.

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 chip-sets from the foundry to sell to outside customers.

This arrangement assures HP 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 with 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."²⁷ By building a long-term relationship, the firms are creating an alliance which allows each to

²⁶ Interview, William Davidow, Partner, Mohr Davidow Ventures, 21 April 1988.

²⁷ Cited in S. Jones, "Hewlett-Packard inks Major Chip Deal," *San Jose Business Journal*, 18 May 1987.

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 that 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 that 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 (reduced instruction set computing) microprocessor is a classic example. A RISC chip uses a simplified circuit design that increases computing speed and performance of a microprocessor.

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 further broke with industry tradition by freely licensing the Sparc design, in contrast with Intel and Motorola's proprietary approach to their microprocessors. The firm established partnerships with five semiconductor manufacturers, which each use their own process technology to produce specialized versions of Sparc.²⁸ The resulting chips share a common design and software, but differ in speed and price. After supplying Sun, these suppliers are free to manufacture and market their versions of Sparc to other systems producers.

As a result, Sun has extended acceptance of its 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 guaranteed customer in Sun and a new and promising product – which they are jointly promoting. Collaboration allowed Sun to reduce significantly 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.²⁹

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

²⁸ The firms are Fujitsu Ltd. (the 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.

²⁹ B. Schlender, "Computer Maker aims to transform Industry and become a Giant," *The Wall Street Journal*, 18 March 1988.

Sun's partnership with Cypress Semiconductor extends such collaboration the furthest. In 1986, the two firms agreed to develop jointly a high speed, high performance version of Sparc. A team of approximately 30 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' integrated circuit 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 of cooperation."³⁰

The two firms benefit from complementary expertise: Sun gained access to Cypress' 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 has not only reduced the cost and spread the risks of developing its workstations, but has been able to bring new products with innovative features and architectures to market rapidly. These relationships prevent competitors from simply imitating Sun's products, and represent a formidable competitive barrier.

This explains Sun's championing of systems which rely on readily available components and industry standard technologies (or "open systems"). Under this approach, computers made by different firms adhere to 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.

As Silicon Valley producers introduce specialized systems 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 minicomputers, engineering workstations, networked minicomputers, personal computers, parallel and multiprocessor computers and specialized educational computers [19]. As long as this process of product differentiation continues to undermine homogeneous mass markets for computers, Silicon Valley's specialist systems producers and their networks of suppliers will flourish.

Conclusions

Technical expertise in Silicon Valley today is spread across hundreds of specialist enterprises, enterprises which continue to develop independent capabilities while simultaneously learning from one another. As computer systems firms and their suppliers build collaborative relationships, they spread the costs and risks of developing new products while enhancing their ability to adapt rapidly to changing markets and technologies.

This is not to suggest that inter-firm networks are universally diffused or understood in Silicon Valley. The crisis of the region's commodity semiconductor producers in the mid-1980s is attributable in part to distant, even antagonistic, relations between the chipmakers and their equipment suppliers [30,33]. Other examples of arms-length relationships and distrust among local producers can no doubt be identified [6]. However, these failures of coordination do not signal inherent weaknesses in network forms of organization, but rather the need for the institutionalization of inter-firm collaboration in the U.S.

Proposals to replace Silicon Valley's decentralized system of production with an "American keiretsu" – by constructing a tight alliances among the nation's largest electronics producers and sup-

³⁰ Interview, Lowell Turriff, Vice-President Marketing, Cypress Semiconductor, 7 March 1988.

pliers [5] – would sacrifice the flexibility which is critical in the current competitive environment. Such proposals also misread the changing organization of production in Japan, where large firms increasingly collaborate with small and medium-sized suppliers and encourage them to expand their technological capabilities and organizational autonomy [13,21,7]. In Japan, as in Silicon Valley, a loosely integrated network form of organization has emerged in response to the market volatility of the 1970s and 1980s.

The proliferation of inter-firm networks helps to account for the continued dynamism of Silicon Valley. While the region's firms rely heavily on global markets and distant suppliers, there is a clear trend for computer systems producers to prefer local suppliers and to build the sort of trust-based relationships which flourish with proximity. The region's vitality is thus enhanced as inter-firm collaboration breeds complementary innovation and cross-fertilization among networks of autonomous but interdependent producers.

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