17

Why the Valley Went First

Aggregation and Emergence in Regional Inventor Networks

Lee Fleming ▪ Lyra Colfer ▪ Alexandra Marin ▪ Jonathan McPhie

It has become increasingly fashionable to identify social networks as crucial contributors to regional innovative capacity (Marshall 1920; Piore and Sabel 1984; Krugman 1991; Stern and Porter 2001). Networks have been argued to offer improved customer-supplier relations, more efficient venture capital and legal infrastructure, and increased knowledge spillovers between firms and regional institutions. Knowledge spillovers are thought to be particularly crucial to fast-developing technologies such as semiconductors and, more recently, biotechnology. Spillovers correlate with increased labor mobility (Angel 1989), relaxed enforcement of non-compete covenants (Gilson 1999), and increased labor mobility and brain drain (Marx et al. 2009, 2011). Saxenian (1994) makes the functional argument connecting networks and innovative capacity, proposing that Silicon Valley's rapid labor mobility, collective learning, interfirm relationships, and informal knowledge exchange gave it a decisive edge in competing against the more secretive and autarkic firms of Boston.

Nevertheless, there is still skepticism about the causal influence of networks in regional innovative productivity. For example, Kenny and Burg (1999) acknowledge that "all business activity is dependent upon networks" but contend that a region's network(s) will adjust to suit its technological competencies over time. Where Saxenian (1994) sees causal differences in Silicon Valley and Boston networks, Florida and Kenney (1990, 98–118) see indeterminate similarity and propose that technological trajectories drive regional advantage. Turning the argument on its head, the skeptics propose that networks result from—and do not necessarily improve—regional innovative advantage (Feldman 2001).

These opposing arguments for and against causality immediately raise the suspicion of coevolution. Surely networks influence regional advantage and are in turn shaped by regional success or failure. But much of the current discussion about networks and regional advantage remains static (for important exceptions, see Owen-Smith and Powell 2004), implicitly assuming that networks differ across regions but remain essentially unchanged within them. If this assumption were untrue—and could be cleanly unpacked—the discussion could be greatly enriched.

With these goals in mind, this chapter has two objectives: first, to understand how isolated clusters of regional inventors become connected, and in particular, why Silicon Valley aggregated earlier than Boston; and second, to describe the information flows and creative ecologies of such networks. We begin by comparing the structural histories of the patented inventor coauthorship networks of Boston and Silicon Valley from 1975 through 1999. Following Fleming, King, and

We would like to thank Ivin Baker, Jeff Chen, and Adam Juda for their help with matching algorithms and illustrations; Christine Gaze for her editing; and the Harvard Business School Division of Research for support. Most important, we would like to thank all the inventors who spent a great deal of time with us discussing their careers.

Juda (2007), we first demonstrate that the largest connected network component in Silicon Valley underwent a dramatic transition in the early 1990s.[1] Although small at first—and similar in size to Boston's largest connected component in 1989—it grew rapidly from 1990 on, encompassing almost half of Silicon Valley's patenting inventors by 1999. Boston did not undergo a similar transition until the mid-1990s, and even recently its largest connected network component remains proportionally smaller, containing approximately a quarter of its inventors. We investigated this historical divergence by focusing on the actual ties that inventors created—or failed to create—across the dominant network components in their regions. To fulfill our second objective, we asked the inventors about the knowledge flows in their careers, both within and across the observed clusters, and how such flows influenced their creativity.

While inventors move from job to job and create collaborative ties for a wide variety of reasons (Gulati and Gargiulo 1999), our data highlight the importance of "academic" institutions in the creation of ties across regional organizations. Much of the difference in aggregation[2] can be traced to Stanford doctoral students taking local employment, in contrast to MIT students leaving the Boston region. We also find that a single institutional program—the postdoc fellowship at IBM's Almaden Valley Labs—was responsible for 30 percent of the Valley's initial aggregation. Young inventors play a particularly important role in the process of regional aggregation; while older inventors move to start-ups (and are less likely to move in general; see Angel 1989), young inventors move from graduate school through private firm postdoc programs and other positions within large network components, bridging technological communities and generating new technological combinations.

With respect to the competing comparisons of the two regions (Saxenian 1994; Florida and Kenney 1990; Kenney and Burg 1999), we found that Silicon Valley's patenting coauthorship networks are indeed more connected—but in some cases less robustly so—than those of Boston. While our interviews indicate that information flowed more freely between firms in the Valley, there were plenty of engineers and scientists in Boston who were also willing to risk management stricture and talk to their colleagues across organizational boundaries. Willingness to share information appears to be more strongly correlated with a managerial versus technical profession than with location.

DATA AND METHODS

To gain empirical traction on the issue of how the social structures of Boston and Silicon Valley differed and the effect this had on the development of their innovative capacity, we consider all patented inventors and their coauthorship relations in the two regions. For our purposes, there is a relationship between patented inventors if they have coauthored any patent over a five-year moving window (alternate window sizes also demonstrated a qualitatively similar emergence phenomenon). This relational definition results in many disconnected components that demonstrate a skewed distribution, with most components of small size and fewer and fewer of larger size. We refer to the largest and right-most component on this distribution as the "largest component." Appendix A contains a description of the matching algorithm we used to identify individual inventors over time (for a later version of this algorithm, see Lai et al. 2011).

Figure 17.1 illustrates the proportion of patented inventors encompassed within a region's largest component.[3] For example, if there were ten inventors in a region and six of them coauthored any patents together in the prior five years, then the proportion in that region would be 0.6 or 60 percent. Note that the relationship is transitive—if inventor A and B worked together on one patent, and B and C on another, then A and C can trace an indirect coauthorship to one another and lie within the same component. If

[1] We define "component" as a cluster of inventors connected by at least one patenting coauthorship tie in the previous five years.

[2] We define the coming together of isolated inventor networks into larger networks as a process of network "aggregation." The term is intentionally dissimilar to the word *agglomeration* used in the economics literature, which refers to economies that firms gain by clustering together and sharing pooled labor availability, infrastructure, suppliers, and other services.

[3] We define a patent as being in a region if at least one inventor lives within that region, as determined by the hometown listed on the patent. Hometowns are classified within Metropolitan Statistical Areas (MSAs) by the U.S. Census Bureau (Ziplist5 MSA 2003). Note that this definition enables inventors from outside Silicon Valley or Boston to be included as regional inventors if they worked with someone who did live within the region. We analyzed a more restricted definition and found only minor qualitative differences in the processes . All graphs include all 337 U.S. MSA regions for comparison and illustrate five-year moving windows.

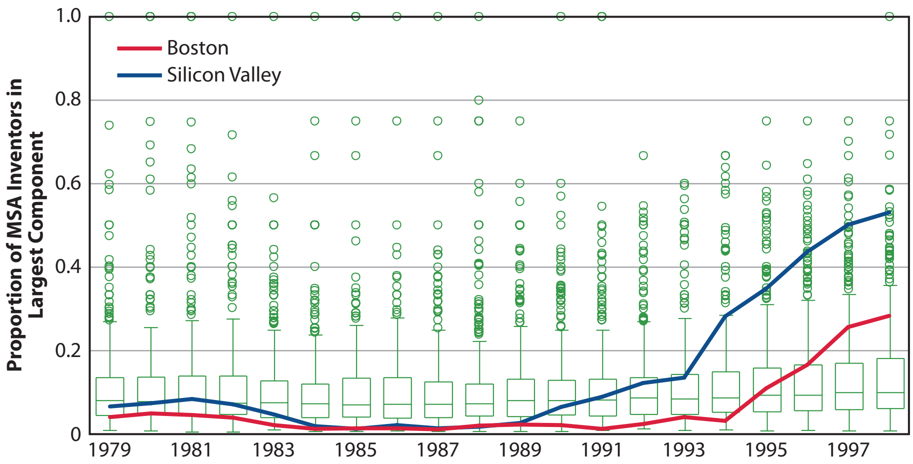

Figure 17.1 Box plots of the size of the largest connected component relative to the entire network of patented inventor collaborations by U.S. Metropolitan Statistical Area (x-axis indicates last year in five-year moving window).

four of the ten inventors had coauthored patents and no other group of coauthors was bigger, then the proportion would be 0.4 or 40 percent. The interesting feature of figure 17.1—and the original motivation for this chapter—is the aggregation process in Silicon Valley. It began in 1990, and by 1998 almost 50 percent of the Valley's inventors had aggregated into the largest component. Boston's aggregation, by contrast, did not begin until 1995, and by 1998 its largest component had only reached 25 percent of the region's inventors.

The histograms of figure 17.2 show which of the prior year's network components aggregated to form the following year's largest component, from 1988 to 1992. Note that the size of any given component is simply the number of inventors it includes. Each region contains thousands of components of varying sizes in any given year (most of which contain just twenty or fewer inventors and therefore fall above the frequency cutoff used for the y-axes in figure 17.2).

Figure 17.2 illustrates the early similarity in the distributions of the two regions' components. In 1988 Boston had a larger largest component (although figure 17.1 obscures this because it illustrates the proportion of inventors and Boston had slightly more inventors in that time period). In 1989 the distributions of the larger components across the two regions were similar. Yet as the 1989 panels of figure 17.2 illustrate, the 1st, 2nd, and 6th largest components merged in the Valley to form its largest component in 1990, while in Boston, only the 3rd, 13th, and 384th largest merged to form its largest component in 1990. By 1992 the largest component in Silicon Valley had over 1,600 inventors, in contrast to Boston's approximately 330 inventors. Furthermore, figure 17.2 shows the extent to which Silicon Valley saw a greater number of smaller and distinct components from one time window merging to form its largest component in the subsequent time window. Even though the process begins with the linkage of larger components, it reaches a critical mass at which the largest component begins to suck in components of all sizes.

Qualitative Methods

We conducted in-depth interviews with key inventors in both regions to understand the historical and social mechanics of the aggregation process. We identified these inventors in two rounds. First, we graphed the largest component of 1990 in both regions to pinpoint the inventors who provided crucial linkages from the previous year's components. For example, drawing on the histograms in figure 17.2, we identified the inventors who connected the 1st, 2nd, and 6th largest components together in the Valley and the 3rd, 13th, 384th, and 707th largest in Boston. We then identified similar inventors who

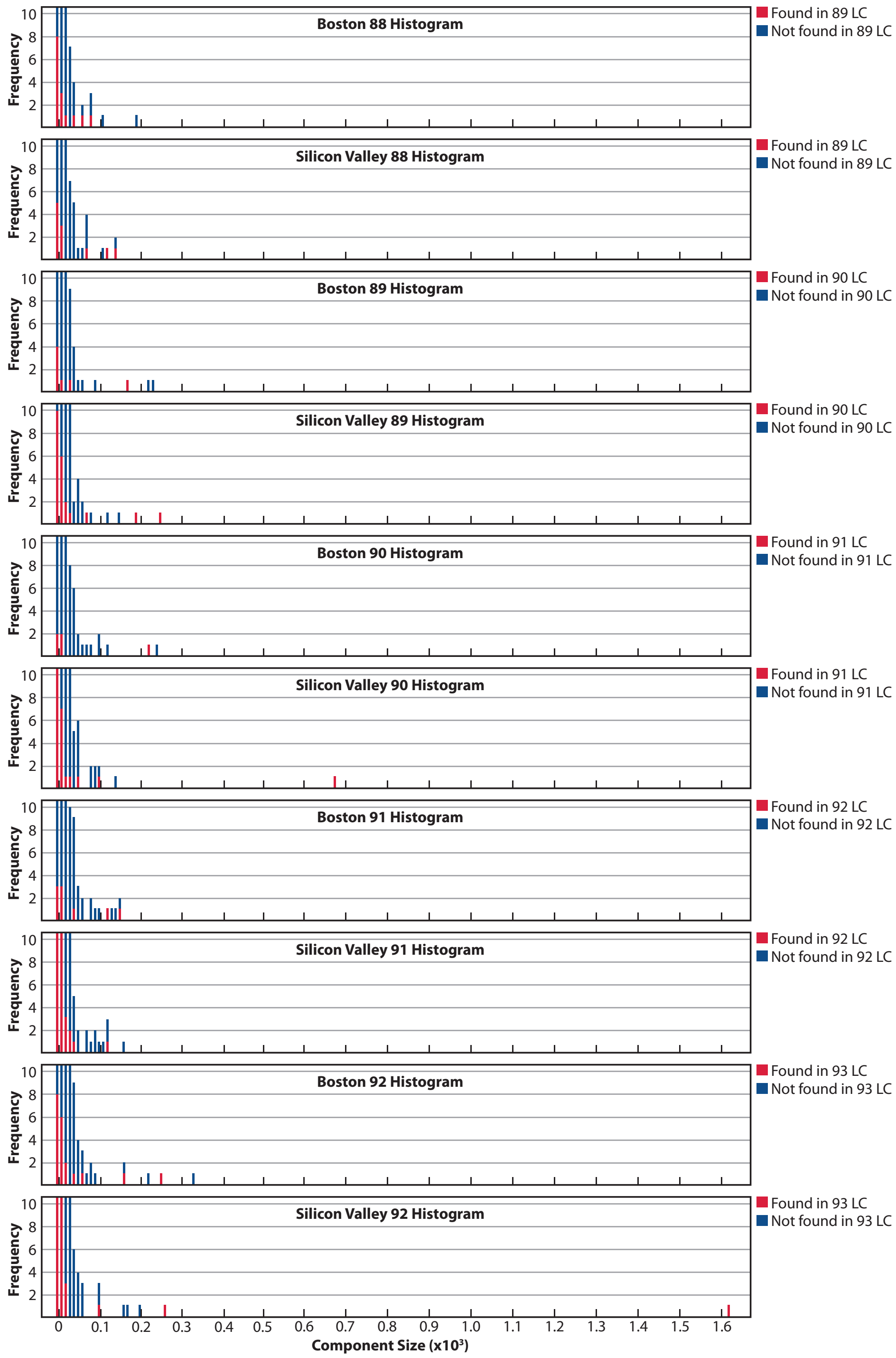

Figure 17.2 Time series of histograms of component size frequency of Boston and Silicon Valley. The x-axis identifies the range of possible sizes (in number of inventors) for network components (demarcated into bins of 10 for readability), while the y-axis reflects, in blue, the number of connected components of a given (bin) size found in that region during that year (truncated to 10 to allow for visibility of the red bars described hereafter) and, in red, the number of those components which merged to become a part of the single largest connected component of that region in the following year. Because of space constraints and to emphasize the right-skewed outliers, we truncated the y-axis of each histogram. Boston generally has a larger number of inventors in the first category—that is, its distribution is more left-skewed—over all the time periods.

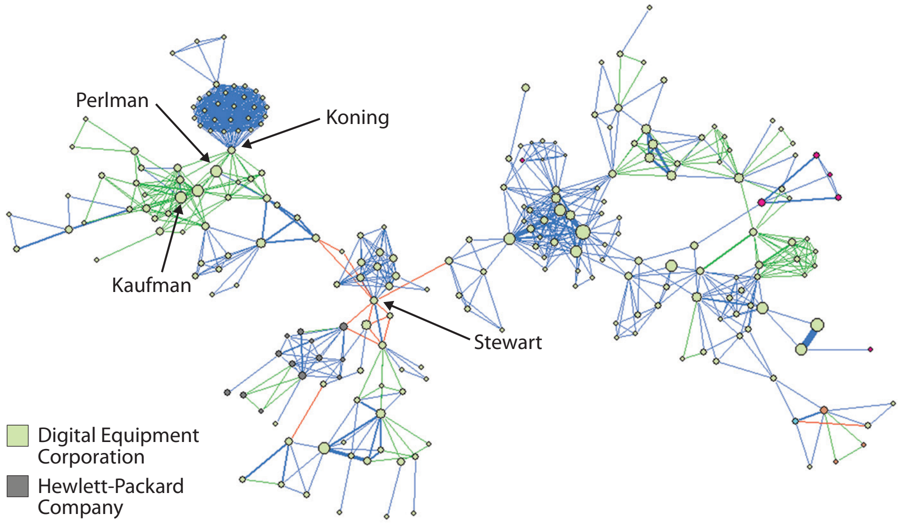

Figure 17.3 Largest component of Boston, 1986–90, by assignee and importance of inventions. The DEC component did not aggregate into the 1990 largest component. (Previously published in Fleming, King, and Juda 2007.)

did not create such linkages between other large components—for example, the 3rd, 4th, and 5th largest components in the Valley and the 1st, 2nd, 4th, and 5th largest in Boston.

We chose this second set of control inventors based on its similarity to the first set of linking inventors. All inventors from components that did not aggregate into the 1990 largest component but were similar in size to those that did were at risk of control selection. We ran a Euclidean distance-matching algorithm (the compare command in STATA) with variables that measured the linking inventor's patenting history. We included variables to measure the inventor's access to information and likelihood of career movement opportunities, such as the mean degree of collaborations, clustering of the inventor's collaborators (a density measure of the actual number of ties between alters, divided by the possible number of ties), number of patents by time period (or basic inventive productivity), and future prior art citations by the time period (since citations have been shown to correlate with patent importance; see Albert et al. 1991). Finally, we interviewed Robert Stewart because of his compelling position at the center of the disintegration of Boston's largest component, as illustrated in figures 17.3 and 17.4.

We were able to contact many of the linking and control inventors we identified. We interviewed them mainly during July and August 2003, presenting the inventors with the histograms shown here and illustrations of their own network components with all of their coauthors identified. We asked them about their careers, what was happening within their component during the time period under study (especially with regard to job mobility), and where their collaborators were now. We asked specifically about the collaborators in their patent networks and about any other networks, such as social or scientific networks.

Follow-up questions probed for inaccuracies in our illustrations and name-matching algorithm and for sampling bias caused by failed patent attempts or by technical efforts that were not intended for patenting. None of our inventors indicated an inaccurate name match or colleagues, and all felt that the illustrated network reflected their patent coauthors accurately. For example, Salvador Umatoy of Applied Materials indicated that a failed project had not been patented but that his collaborators on successful patents were all reflected; Jakob Maya, a lighting scientist, noted that some of his projects concluded with published papers rather than patents, as did Radia Perlman and Charles Kaufman (both computer engineers originally with Digital Equipment Corporation [DEC]), but none recalled any patent collaborators who

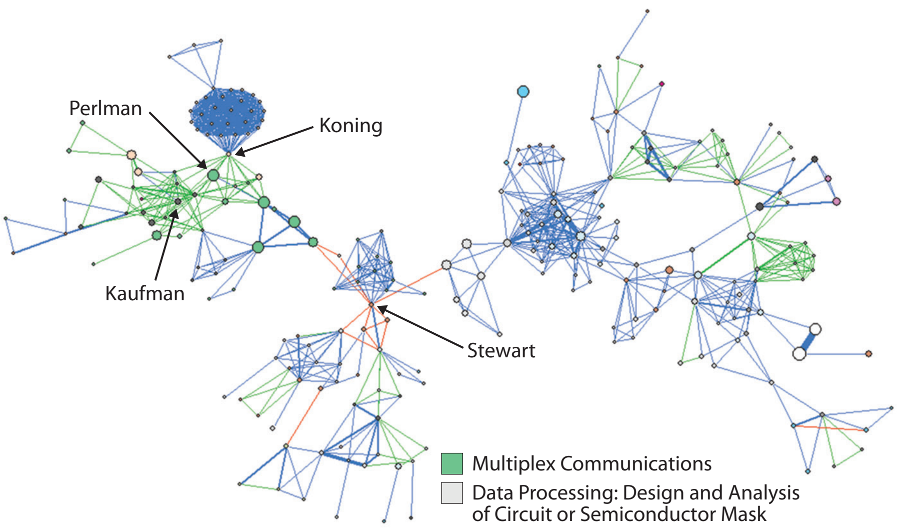

Figure 17.4 Largest component of Boston, 1986–90, by technology type and usage of scientific literature. The DEC component did not aggregate into the 1990 largest component.

were not represented in his or her network component as illustrated. Given evidence from patent citation data that information flows across indirect linkages (Singh 2005) and that aggregation processes improve regional inventive productivity (Fleming, King, and Juda 2007), we also asked the inventors about information flow across the illustrated linkages (the second motivation for this chapter). Finally, we simply asked them what they thought might have caused the aggregation processes we observed.

To supplement these detailed analyses of the individual components, we also investigated plausible alternatives. Additional analyses of the patent data (available from the first author) showed that Boston inventors were slightly more likely to work alone, be self-employed and therefore own their own patents, and work with a fewer number of collaborators. There were only slight differences in tie density over time for the two regions, in the age and diversity of technology, and in the number of assignees per inventor for the two regions. Fleming and Frencken (2006) explicitly investigated inventor mobility between the regions and found that mobility was slightly higher in the Valley in 1975. The difference in mobility steadily reversed, however, such that differences were negligible in 1990.

Most important, none of these potential causes demonstrates an abrupt transition around the time of study that might have caused the aggregation processes we observed. Finally, even though universities as a whole were patenting more over the time period than they had before, the elite schools such as Stanford and MIT did not change their patenting rates very much (Mowery et al. 2001). Also, given that Boston had more university patents than the Valley did, this may well have increased aggregation in the region, as inventors left school and took local employment.

Qualitative Data

Our interviews with the Valley and Boston inventors revealed both common and region-specific reasons for aggregation and non-aggregation. We organized these reasons by regions and whether the cause was specific by region. These reasons are summarized in table 17.1. We did not hear of any exactly similar aggregation processes, although we will discuss the obvious similarities among the stories that follow. The Silicon Valley–specific reasons for aggregation included an IBM postdoc program and local hiring of local graduates. Boston-specific reasons included internal collaboration within DEC. Common non-aggregation reasons between the regions included the instability of big

Table 17.1.
Summary of Reasons for Aggregation and Non-aggregation in Silicon Valley and Boston

	Aggregation	Non-aggregation
Silicon Valley	Local graduate employment IBM postdoc program	Internal labor markets Start-ups Big firm instability Self-employment
Boston	Internal collaboration	Internal labor markets Start-ups Big firm instability Non-local graduate employment Lack of internal collaboration Non-local internal collaboration Patenting/publication policies

firms, internal labor markets, and the movement of personnel to start-ups. Valley-specific reasons for non-aggregation included the movement of personnel to self-employment, while Boston-specific reasons included non-local graduate employment, lack of internal collaboration, internal firm collaboration that was non-local, patenting policies, and product life cycles.

Valley-Specific Reasons for Aggregation

We identified two aggregation processes unique to Silicon Valley, both driven by IBM. The company hired local doctoral graduates, connecting it with Stanford components, and it sponsored a postdoctoral fellowship program, connecting it to the large pharmaceutical and biotech component in the Valley. Figures 17.5 and 17.6 illustrate the largest component of the Valley from 1986 through 1990.[4]

IBM's Almaden Valley Research Lab provided the stable backbone of the 1990 Silicon Valley aggregation. IBM constituted the largest component in the Valley by 1987 and remained the largest component in 1988 and 1989 (in contrast to the unstable backbone of the Boston aggregation process, a point to which we will return later). Stanford's Ginzton Applied Physics Lab network joined the Valley's largest component in 1989 through the career of William Risk. Upon graduation from Stanford with a Ph.D. in electrical engineering, Risk accepted employment (and obviously patented) at IBM.[5] Further Stanford aggregation occurred in 1990 with William Kozlovsky's graduation and departure from Professor Robert Byer's lab. Hence these multiple ties created a robust conduit of inventors and ideas from Stanford to IBM.

William Risk and Professor Gordon Kino[6] elaborated on the mobility of students and the resultant knowledge flows.[7] Kino reported that his students of that era had gone on to a variety of academic and technical positions, including start-ups in the Valley and in Oregon, self-employment as an entrepreneur in Wyoming, academic positions at Stanford, UC–Santa Barbara, and Wisconsin, and employment at Tektronix, Bell Labs, AT&T, and IBM New

[4] Each node corresponds to an inventor and network ties correspond to coauthorship of at least one patent. A1 colors the nodes by firm and A2 colors them by technology (only A2, A7, and A14 are in full color; other pictures are grayscale. Node size in A1 corresponds to future prior art citations to the inventor's patents over the five-year time period and can be interpreted as the importance of the patent holder's inventions (Albert et al. 1991). Node size in A2 indicates the number of non-patent (generally scientific) references. Tie strength corresponds to coauthorship strength, as measured by the number of coauthored patents, normalized by the number of inventors on the patents. Tie color corresponds to tie age: green ties were formed in the prior year, blue ties in the second through fourth prior years, and red ties were formed five years prior. All network diagrams were plotted in Pajek with a directed force algorithm (Batagelj and Mrvar 1998).

[5] William Risk is still at IBM Almaden Research Laboratory and has done research in applied physics, optics, and photonics.

[6] Gordon Kino received his Ph.D. from Stanford University in 1955 and has done research in nondestructive testing, fiber optics, fiber-optic modulators, fiber-optic sensors, and optical, acoustic, and photo-acoustic microscopy. He is a member of the National Academy of Engineering.

[7] Technically the agglomeration between Gordon Kino of Stanford and William Risk of IBM occurred one year earlier than the 1986–90 window. Given that we were unable to meet with William Kozlovsky and Robert Byer and given that the Stanford-IBM inventors knew each other well and corroborated the processes described here (Kozlovsky did so in a phone interview), we report from Kino and Risk. Given that a very similar process occurred twice over two years, it would appear to be a robust and frequent occurrence.

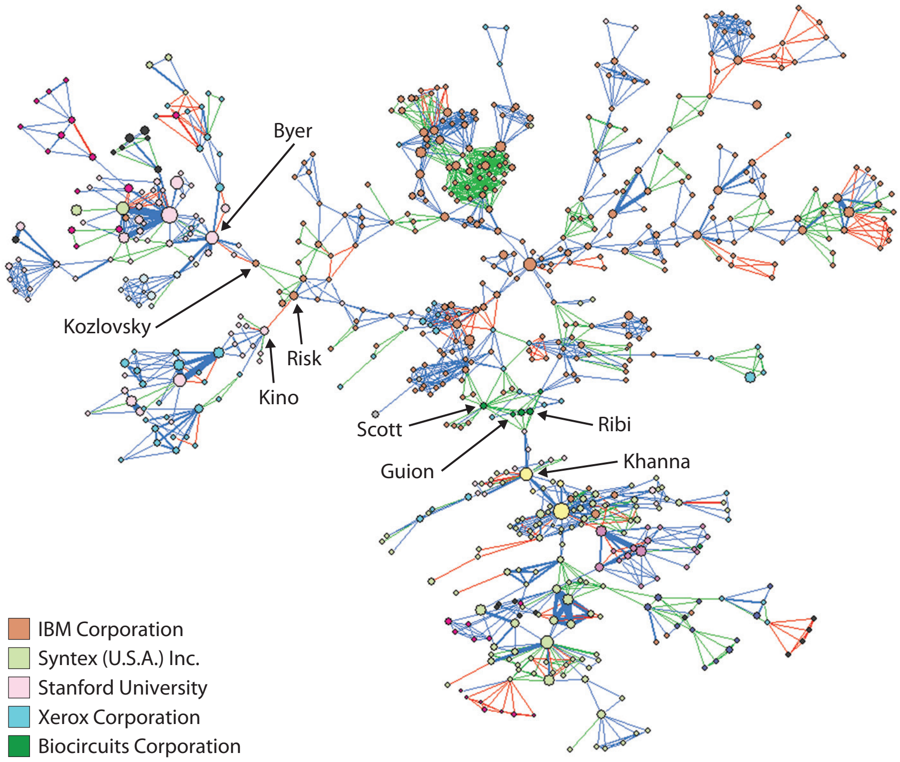

Figure 17.5 Largest component of Silicon Valley, 1986–90, by assignee and importance of inventions. Node sizes indicate the number of future prior art cites to an inventor, normalized by the number of collaborators. Tie width reflects the number of collaborations, tie color indicates age of tie (red is five years prior, blue is two to four years prior, and green is prior year), and colors indicate assignee (generally a firm or university). Yellow nodes in lower right indicate Abbott Laboratories, to which Pyare Khanna (along with Edwin Ullman) moved to late in the time period. Graphed in Pajek with Kamada-Kawai/Free algorithm (Batagelj and Mrvar 1998). (Previously published in Fleming, King, and Juda 2007.)

York. He and his students studied microscopy, acoustics, photonics, and microwave phenomena, and his students went on to work in a wide variety of industries, including medical instrumentation, electronics, optics, and scientific instrumentation. Professor Kino's description of local employment for Stanford graduates appears to be the flip side of Professor Richard Cohen's description below of non-local employment for MIT graduates. As such, the processes of local and non-local employment of graduates surely operate similarly across regions—when appropriate local firms are hiring, graduates are more likely to stay, and when they are not, or if the region lacks such firms, graduates emigrate. For example, William Risk stressed the importance of optics to a wide variety of industries and how the Valley provided a great diversity of technological applications and industrial opportunities.[8]

Kino and Risk renew old ties at conferences and visits (Risk had visited Stanford the week prior to the Kino interview). The former students and their professors discuss technical work at conferences even though they work for different firms. With the exception of Kino's formal consulting relationships, neither Kino nor Risk remembers other substantial or formal technical information flows. Both agreed that the technical information only flows through a strong,

[8] Even though Angel (1989) provides some evidence that Valley firms are more likely to hire local graduates than are firms in other regions, our categorization of such local hiring processes as Silicon Valley–specific is mostly an expositional convenience, based on our interview sampling and the economic conditions at the time.

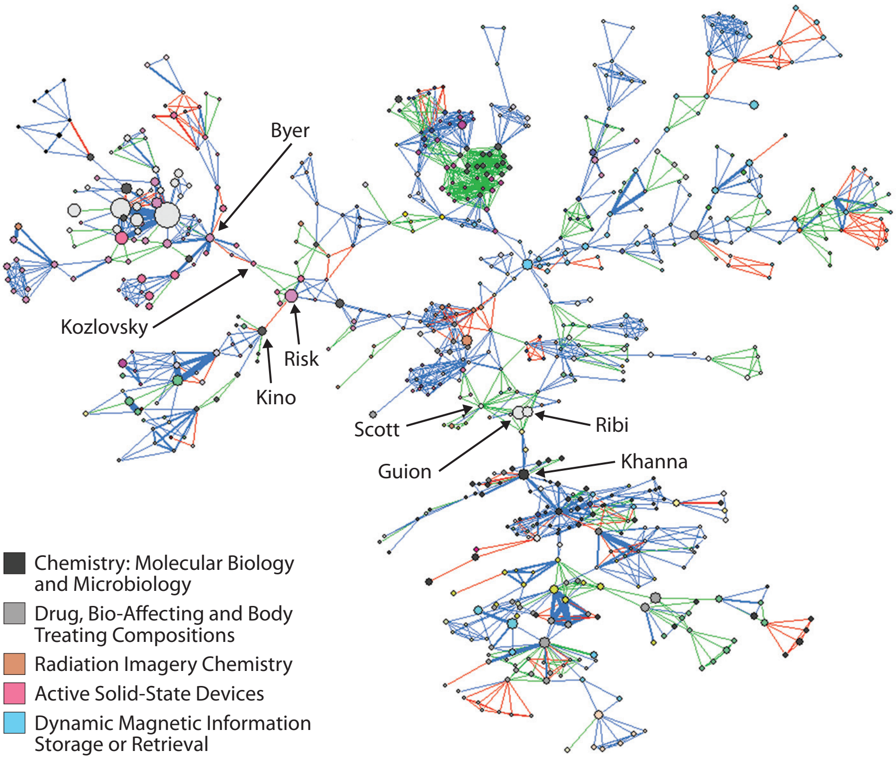

Figure 17.6 Largest component of Silicon Valley, 1986–90, by technology type and usage of scientific literature. Node sizes indicate the number of references to non-patent literature by an inventor (mainly peer reviewed science), normalized by the number of collaborators. Tie width indicates number of collaborations, tie color indicates age of tie (red is five years prior, blue is two to four years prior, and green is prior year), and colors reflect U.S. Patent Office technology class. Graphed in Pajek with Kamada-Kawai/Free algorithm (Batagelj and Mrvar 1998).

informal social network. In particular, they felt that graduates from the Ginzton Applied Physics Lab at Stanford had maintained particularly close contact since leaving Stanford.

The largest aggregation occurred with the linkage of the second-largest component in the Valley—Syntex (a research-intensive pharmaceutical firm) and smaller biotech firms—with IBM in 1986–90.[9] The actual connection was indirect and occurred indirectly through the career of John Campbell Scott[10] and the (now failed) start-up of Biocircuits.

Scott described how the Almaden Lab hired postdocs straight from school (generally PhDs but other degrees as well) with the intention that they would leave for employment with another private firm after one or two years. Modeled after academia and similar programs at Bell Labs, the practice was intended to seed the technological community with experienced IBM-friendly scientists. Such a process would obviously create observable ties between IBM and a wide variety of other firms. Unlike the departure of senior inventors from large and established firms for start-ups (which does not create ties between

[9] Even though Silicon Valley is known in this time period as a center of semiconductor and computer technologies, only the 1st and 5th largest components covered such technologies, namely magnetic media (computer disks at IBM) and semiconductor manufacturing equipment (at Applied Materials). The 2nd, 3rd, and 4th largest components consisted of pharmaceutical (Syntex), polymer chemistry (Raychem), and optical (Xerox PARC/Spectra Physics, Hewlett Packard) technologies.

[10] John Campbell Scott still works at IBM Almaden Research Laboratory. He earned his Ph.D. in solid state physics at the University of Pennsylvania and has worked in materials science for most of his career.

large components), the postdocs found future employment across a variety of firms. Hence the IBM postdoc program played a crucial role in the initial and continuing aggregation processes in the Valley because it linked large components to other large components.

While the connection of the Syntex and IBM components relied on the postdoc program, it actually occurred through the career of a young inventor at Biocircuits, an early (and ultimately failed) electronics-biotech start-up that developed biosensors.[11] Todd Guion, a Stanford graduate in chemistry, worked for Scott during his postdoc at IBM and then took a job at Biocircuits. Victor Pan took a similar path from San Jose State and Santa Clara University through IBM to Biocircuits. Biocircuits was attempting to build a biosensor based on polymeric material and wanted to get a charge through a polymer. Guion thought that optical technology might help and recommended to Hans Ribi,[12] the CEO of Biocircuits, that he contact Scott for help. After some initial difficulty, Scott secured permission from IBM management to act as a scientific adviser, given that there were no apparent conflicts of interest. Scott spent many days at Biocircuits and interacted with most of its employees. He suggested the use of bio-refringence associated with specific binding to solve the problem. He reported that he "definitely learned a lot of interesting things" that he is now, many years later, applying as IBM moves into biological technologies. He had no interaction with Pyare Khanna,[13] however, the prominent pharmaceutical inventor on the other side of the Biocircuits bridge.

Hans Ribi, a Stanford graduate in biochemistry and the owner/CEO of Biocircuits, had a much less positive view of information flow across collaborative linkages, believing that it should not and generally does not occur. He argued that patents are used to protect proprietary property and that coauthorship did not indicate a higher probability of information flow. Interestingly, the manager on the other side of the IBM-to-biotech/pharma connection, Pyare Khanna, also complained about the possibility of information flow. Both Ribi and Khanna were managing start-ups at the time of the interview and felt much more vulnerable to the loss of proprietary information and key individuals, in contrast to the IBM scientists who, as "good corporate citizens," felt resigned to the possibility of such loss.

Boston-Specific Reasons for Aggregation

We identified only one Boston-specific reason for aggregation. The largest component in 1990 resulted from internal collaboration—newly initiated interaction of smaller work groups—within Digital Equipment Corporation, as illustrated in figures 17.3 and 17.4. We describe the integration of the DEC component through the careers of Charles Kaufman, Paul Koning, Radia Perlman, and Robert Stewart.[14]

Charles Kaufman, discussing his own role as a "point of connection" in these processes, noted that he was particularly likely to be responsible for information flow across multiple departments of DEC for two reasons. First, he was one of "the gang of four" chosen from four distinct working groups to design DEC's "next generation of security." Second, while he was a software engineer by trade, he often socialized with those working in hardware. Paul Koning, addressing the same question, noted that his shifting collaborators usually corresponded to shifting task assignments but that two exceptional features of working at DEC could explain some of his more interesting collaborations. First, his working group's manager

[11] The start-up might be described as a forerunner of today's combinations of biological and digital technologies, seen in products such as Affymatrix's combination of assay and semiconductor technology into a gene array chip; in publications, such as *BIO IT World*, that focus on the application of computing power to biological and genomic problems; and in research laboratories, such as Stanford's BIO-X, that hope to encourage collaboration between chemistry, engineering, biological, and medical research. Pyare Khanna felt that Biocircuits failed because it was too early and the integration was too difficult.

[12] Hans Ribi received his Ph.D. in biochemistry at Stanford University in 1988 and was the CEO of Biocircuits at the time that Todd Guion suggested that John Campbell Scott work with the firm.

[13] Pyare Khanna worked at Syntex as a senior scientist during the period of the study. He is currently the CEO of Discoverx, a drug target company in Fremont, California.

[14] Charles Kaufman attended Dartmouth for mathematics and worked with a Dartmouth-related technology venture prior to accepting a position in the network architecture group at DEC. Paul Koning worked with Charles Kaufman and Radia Perlman at DEC before moving to smaller start-up ventures. He is currently the founder and CTO of a successful VC-backed start-up just outside the Boston area. Radia Perlman earned her Ph.D. from MIT while employed by DEC. She is currently a Distinguished Engineer at Sun Microsystems and serves on the Internet Architecture Board of the Internet Engineering Task Force. Robert Stewart earned undergraduate and master's degrees in electrical engineering from MIT. He took employment with DEC upon graduation and remained with the firm until its purchase by Compaq. We interviewed Stewart because he was so central to the disintegration of DEC in 1990. He did not meet our typical criteria of being either a bridging node that caused aggregation or a bridging control node.

routinely sought brainstorming solutions from a wide distribution of engineers. Second, co-inventor Radia Perlman's collaborative style of brainstorming made her a particularly strong candidate for generating information flow during this process (as much with him as with other individuals), as did her tendency to prefer topics and projects "at the boundary of academic research and engineering." On the other hand, Koning also noted that Perlman was probably unable to patent much of this work when the participants spanned company boundaries. Both Kaufman and Perlman independently confirmed this viewpoint, enumerating several bureaucratic obstacles they have had to surmount in order to work together since leaving DEC. One particularly interesting example required both parties to persuade their respective employers that their joint invention, while worthy of patenting, was not worthy of commercial sale.[15] Like Scott in the Valley, these Boston inventors overcame legal, managerial, and strategic obstacles to collaboration across organizational boundaries.

Koning and Kaufman both reported switching job functions within DEC several times,[16] typically to new technologies where the knowledge of earlier collaborators proved less useful. Koning often maintained loose ties with prior collaborators throughout this process, occasionally passing back information about old projects but rarely requesting help or technical advice from his old network. On the other hand, he also noted that he and Perlman are a significant exception to this trend because they have continued to collaborate in new ways (e.g., on multiple academic papers and publications) for well over a decade now, despite working for different employers since 1993.[17]

Common Reasons for Non-aggregation

Some of the explanations we heard for non-aggregation between components were common to both regions. First, large established firms with internal labor markets generally retain their employees (Angel 1989). Second, successful inventors from established firms generally go to start-ups rather than to other large established firms. This implies that they will link established firms with large components to start-up firms with small or nonexistent components rather than linking large components to other large components. Finally, when established firms become unstable, they do not hire and their current inventors often spend more time protecting their jobs or seeking new ones than they do inventing. This will be reflected in a decreased rate of patenting and thus in smaller components.

Salvator Umatoy's[18] career matched the explanation for Applied Materials' (the fourth largest component in the Valley) failure to aggregate. The firm's business boomed during the time period under study and there were many internal technical and managerial opportunities for its employees. (Even now, during much tougher times, it retains a strong internal labor market and hires mostly new college graduates.) Applied Materials provided its employees with generous incentives, such as stock options, to stay within the firm. Most of the colleagues in Umatoy's network there (figure 17.7) remained with the firm and—at the time of our interviews—were still technical contributors or had become senior managers, working in close proximity to each other ("he works down that aisle . . . he works in the building next door"). Umatoy commented that only managers went to other large firms; senior engineers went to start-ups (which further inhibited aggregation). When asked about people in his network with whom he had not patented at the time and who had left (part of our concern about sampling bias), he mentioned an engineer who left technology and the Valley altogether and a technology process manager who left for IBM. Umatoy did not work directly with this manager (he was not illustrated in the figures). This memory serves to bolster Umatoy's earlier conjecture that engineers left for start-ups and only managers left for other large firms. Umatoy expressed mixed opinions about information transfer across firms. He also felt that Applied Materials did not "give you time for any outside life [that would enable knowledge transfer]." Yet he reported that before starting a project, Applied Materials engineers do call their

[15] This joint invention was a strong password protocol they created specifically to serve as a free alternative to two patented protocols. Both of their employers agreed not to patent it and they published a paper to place the protocol into the public domain.

[16] Koning reported switching firms several times, choosing one start-up after another, two of which he founded.

[17] Lotus Development acquired Koning's employer, Iris Associates, in 1994; IBM acquired Lotus Development in 1995. Despite these changes, Kaufman continues to work with the same group, now under the IBM umbrella.

[18] Salvador Umatoy (control to Glenda Choate, a bridging inventor at Biocircuits whom we were unable to locate) worked in the medical instrumentation industry before coming to Applied Materials in the early 1980s. He remains there and currently manages mechanical engineers designing wafer fabrication equipment.

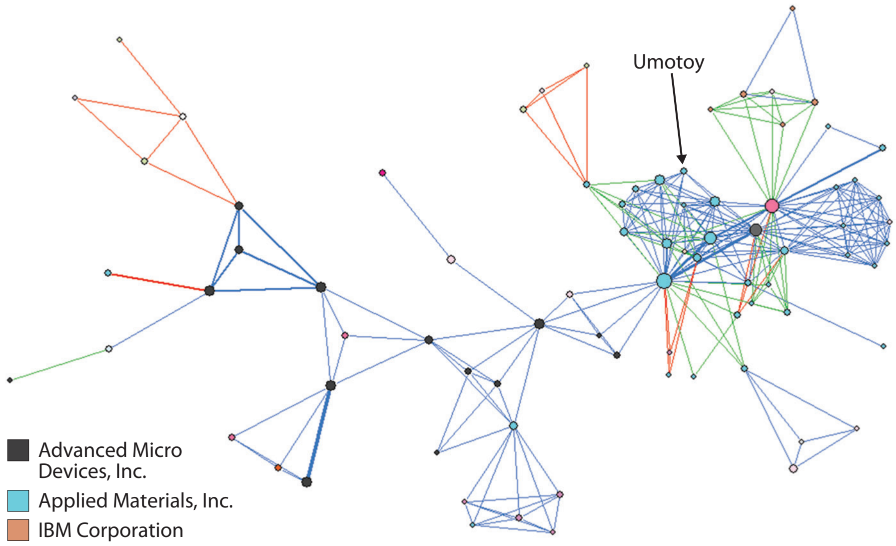

Figure 17.7 Applied Materials component, Silicon Valley's fifth largest component in 1989, by assignee and importance of inventions. Applied Materials did not aggregate into the 1990 largest component.

friends (including colleagues at other firms), contact professors at universities, and read the patent and scientific literature.

In contrast to the seeming lifetime employment at Applied Materials, most of the inventive colleagues of Robert Sprague[19] have left the legendary Xerox PARC. He listed a variety of destinations for his coauthors during the period of study, including Spectra Diode Labs (figure 17.8), Komag, Exxon Enterprises, Canadian Research Corporation, and a variety of start-ups. Most became CEOs, CTOs, or chief scientists, and they often left with the core technology they had invented at PARC. He could not remember any colleagues who left for an established firm, mainly because the start-ups provided stock opportunities. He divided the movement of technology out of PARC into three categories: disgust, opportunities, and friendly, the last category being sponsored and supported by Xerox. He included Spectra Diode Labs and his own, Michigan-based start-up, Gyricon, in the last category. While Xerox might have done a better job in commercializing its PARC technologies, Sprague did not express resentment at the mobile inventors and the spillovers they caused.

We heard similar stories about the power of internal labor markets from our Boston inventors. In addressing why the DEC component did not remain the largest after 1993,[20] Charles Kaufman observed that DEC was not hiring, due to its economic concerns,[21] and that leaving was considered "kind of 'traitorous.'" In fact, he noted that DEC had an explicit policy that employees who left were not to be rehired and he recalled few people leaving before formal layoffs began in 1991.[22]

Despite the increasingly gloomy economic climate along Route 128 during the latter half of the 1980s, the DEC inventors did not recall perceiving any risk to their own careers at the time. They recalled many alternative opportunities available to them, both in Silicon Valley and along Route 128, but they preferred staying at DEC for several reasons. While Kaufman noted

[19] Robert Sprague (control to Pyare Khanna) earned his Ph.D. in physics from the University of Rochester. He has worked at Xerox PARC since the period of study and is CEO of Gyricon, a Xerox PARC spinout.

[20] As mentioned in an earlier footnote, the GTE/Siliconix component displaced the DEC component to become the largest in Boston in 1991. Thereafter, the DEC component resumed its rank as largest in 1992, only to be displaced a final time in 1993. All three of the bridging inventors at DEC with whom we spoke departed in 1993.

[21] At the same time, he also pointed out that he himself had been hired during a freeze and perceived that such exceptions were not particularly rare.

[22] Drawing on the first author's anecdotal experience at Hewlett Packard, he remembers many of his lab's best engineers leaving for an early pen-computing start-up. They were rehired following the start-up's failure and given a party upon their return.

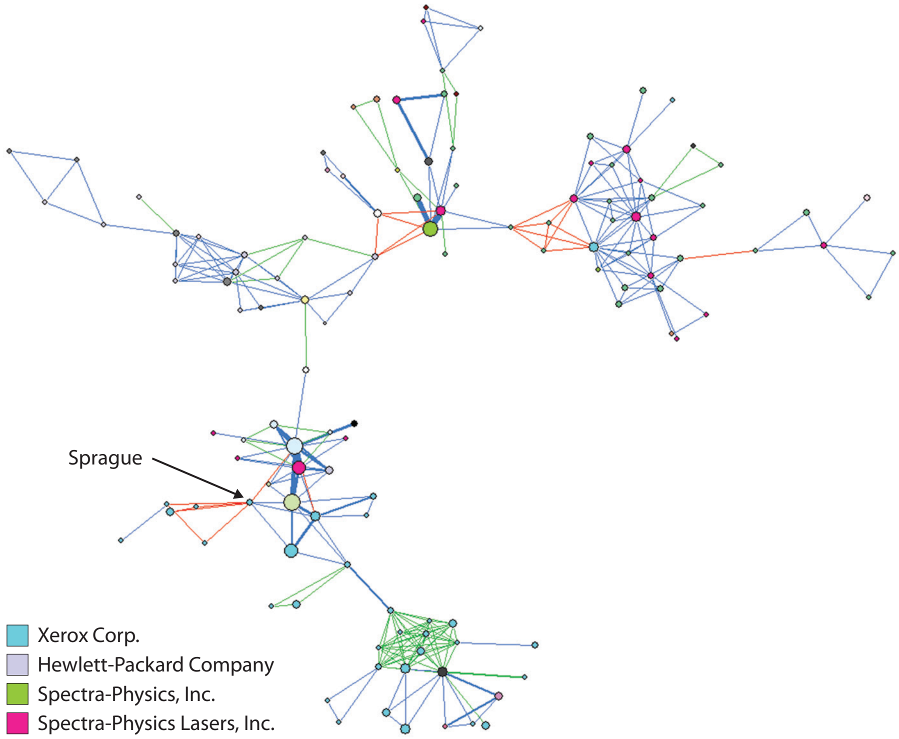

Figure 17.8 Xerox PARC and Hewlett Packard component, Silicon Valley's fourth largest component in 1989, by assignee and importance of inventions. This component did not aggregate into the 1990 largest component.

that DEC had a reputation for treating its engineers particularly well and that no other offers he received at the time could match DEC's compensation, Koning and Perlman also emphasized that their collaborators were still sharp, their work was still innovative, and they were still being given opportunities with the potential for large-scale impact. In fact, both Koning and Perlman specifically described their small work groups within DEC as being rather "start-up like," explaining that despite suffering its share of bureaucratic dysfunction, DEC had "portions" that were still very successful and exciting, at least technologically speaking, even then. All three remained at DEC until 1993, acknowledging that they had stayed on well after the headlines on the business pages of the *Boston Globe* had soured.

Valley-Specific Reasons for Non-aggregation

Michael Froix[23] provided the most interesting career story and uncovered the one Valley-specific story explaining non-aggregation. Raychem—neither a semiconductor firm nor a computer firm but a large and established polymer chemistry firm—had been the Valley's largest component until it was overtaken by IBM in 1987. Froix took his first job in the Valley with Raychem as a senior scientist in 1979 and left in 1985 as a lab director. According to Froix, the firm had initially provided an environment where inventors could work on anything that would lead to a business. This changed in 1983, however, when non-technical management assumed control. Without technical foresight from management, Froix felt that politics became rampant and this caused many senior inventors and scientists to leave. Destinations included medical device and fiber-optics firms, small start-ups, and medium-sized firms such as JDS Uniphase. This was unfortunate for Raychem because it was the only large company in the Valley with polymer expertise at a time when polymer applications were "exploding" in the medical, optical, and

[23] Michael Froix (control to William Risk) earned his Ph.D. in physical chemistry from Howard University. He has worked at Xerox, Celanese, Raychem, Cooper Vision, and Quanam, and has been a very successful independent inventor.

chip and board fabrication industries. In Froix's opinion, Raychem's management repeatedly failed to seize these opportunities. For example, Advanced Cardio Systems asked for help in applying Raychem's electron beam techniques to the medical pacemaker market—which was unrelated to Raychem's current markets—yet Raychem management turned down the request for the purported fear of losing advantage in their current markets.

Froix left Raychem in 1985 out of frustration with no job but a part-time teaching position at the University of San Francisco (USF). He decided to invent a material that would decrease the clotting that occurred on the surface of an artificial heart (recipients of such hearts would generally survive the first few weeks, only to suffer strokes caused by such clots). He worked after hours in a friend's corporate lab. He had approval, since his friend was the founder, but Froix supplied all his own materials, had no access to proprietary information, and did not interact with the employees. He also worked in the lab of a supportive professor at USF. He then read about an analytic technique to measure the effectiveness of his material, developed by Channing Robertson at Stanford. He contacted Professor Robertson in 1986 and asked for help. Robertson replied that he would leave the decision to his best graduate student, Seth Darst (now a professor at Rockefeller University). Darst agreed to help but, like a typical graduate student, didn't begin working until midnight. Undeterred, Froix would sit on the stairs next to the lab from 6:00 P.M., when the building was locked, until Darst arrived many hours later. The collaboration worked well and Froix perfected his invention,[24] sold his technique to Cooper Vision, and helped implement its application to a corneal implant product. He was then introduced to a Stanford cardiologist, Simon Stertzer, and began working on a drug-delivery stent in his garage in Mountain View and at Stanford. He formed a start-up, Quanam, which has been bought by Boston Scientific.[25] According to Boston Scientific's chief technology officer, the technology has become an important part of the firm's product portfolio (Cohen 2003). Froix is now working with a molecular biologist on tissue generation with stem cells.

As can be seen in figure 17.9, Froix did not have many collaborators at Raychem, but he has stayed in touch with them and other former colleagues over the years. Although this was mainly for job searches, he has also discussed technical matters within this network over the years. Froix's experience provides a compelling story of inventive tenacity in the interstices of a technological ecosystem. It is difficult to understand how representative his experience was, however, without a better understanding of the sampling distribution of inventors and their likelihood of their bending corporate and university rules. The Valley might be more supportive of such inventors, but Boston inventors may also have had after-hours access to corporate and university laboratories and there may have been professors at MIT or Harvard who were willing to support their research. Determining how widespread such practices are, in Boston or any other region, would require inventors to admit to violations of corporate and university rules, possibly putting their jobs at risk. Hewlett Packard had an oft-repeated story (told by the protagonist in Packard 1995) about the founders coming in on the weekend and finding the central lab supplies locked. They sought out a security guard, had the padlock cut, and ordered that lab supplies should never again be locked. They felt that supporting an inventor's creativity outweighed any employee theft that might occur. Such stories remain anecdotal, but they consistently suggest that strong engineering and science cultures (wherever they might be) place creativity before financial and proprietary concerns.

Paul Koning expressed skepticism regarding such a generous flow of information or resources across collaborative linkages; he specifically felt that Froix's story was incomplete. In comparing his own more mundane stories of cooperative exchange with accounts of fledgling entrepreneurs slipping into the offices of established firms to borrow slack resources on the late shift, Koning doubted the underlying truth of these anecdotes. While such stories might be true to a point, he contended, surely there was always some form

[24] Professor Robertson, now a dean in the Stanford School of Engineering, did not recall Froix specifically. "There were so many people who contacted me over the years," he explained, "I can't remember them all. I have no reason to believe the story isn't true." Darst corroborated Froix's description via email.

[25] Froix supported other inventors as he had been supported. "When I was running Quanam, I met a physicist on the tennis courts. He had some ideas about a new approach to a surgical cutting device. I made the Quanam labs available to him to carry out some of his experiments and to evaluate prototypes of his devices. My view on this was, and still is, it's always a lot of fun and it is very stimulating to have bright creative people around. Neither I nor Quanam had any proprietary interest in his technology, nor did we desire any such interest. Understanding the science of what he was doing and being in a position to help him was the only consideration."

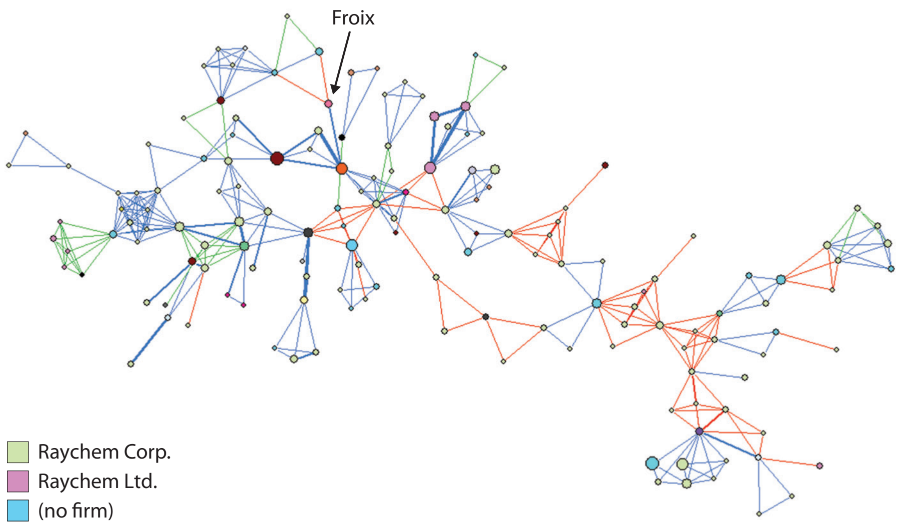

Figure 17.9 Raychem component, Silicon Valley's third largest component in 1989, by assignee and importance of inventions. Raychem did not aggregate into the 1990 largest component.

of unseen equity relationship underlying this seemingly informal cooperative behavior.

Boston-Specific Reasons for Non-aggregation

We found seven reasons for Boston's non-aggregation. First, MIT graduates tended to take academic and private sector jobs outside the Boston area, despite the wide variety of academic opportunities available there. Second, MIT graduates went to smaller firms in the medical device industry, so their mobility did not link large clusters.

Third, continued aggregation of the DEC component was hampered by management's encouragement of internal rivalry and competition. Fourth, engineers at Honeywell, another large component in the time period, only collaborated with Intel inventors and other Honeywell inventors outside the region. Fifth, the pensions at older firms penalized mobility. Sixth, the heavily academic focus of the Boston area resulted in less emphasis on patenting and more on the publication of scientific papers. Finally, some firms patented reluctantly in order to control costs.

Whereas the IBM component emerged by 1987 to serve as the underlying foundation of the largest Valley component in all subsequent years, the composition of the largest Boston component shifted from one year to the next until 1993.[26] The immediate cause of this instability is dramatically illustrated by the career of Robert Stewart in figures 17.3 and 17.4. Stewart is the only inventor who integrates the three major subcomponents at DEC. He (2004) indicated that his integrating role arose from his popularity as a design reviewer across different DEC product lines. While these design reviews did not create the observed ties, they made Stewart and other technical leaders aware of where the experts were located in the corporation. When Stewart or other smart colleagues had a question or problem that might benefit from collaboration, they knew whom to contact. These contacts then resulted in the observed ties. As illustrated by the red color of Stewart's ties, however, they are all five years old. The abruptness of DEC's structural disintegration was caused by the product life cycle. DEC's lawyers generally filed all necessary patents the night before a product shipped. In this case, the upper and right ties had been created with the shipment of the Nautilus project in early January 1986. In addition to the Nautilus project ties, the lower left tie had been one of many collaborations between Stewart

[26] The GTE/Siliconix component, which was 2nd largest in 1989 and 1990, actually displaced the DEC component to become the largest in Boston in 1991. Thereafter, the DEC component resumed its rank as largest in 1992, only to be displaced a final time in 1993 by the merging of one portion of the former 1989 largest component with several other mid-sized components to create a single aggregation of inventors across organizations as diverse as MIT, Polaroid, Reebok, Kopin Corp., Motorola, Mobile Oil, and United States Surgical Corporation, among many others.

and the R&D and networking groups and just happened to expire at the same time.

During the 1985–89 window, the largest component in the Boston network consisted primarily of MIT affiliates. Richard Cohen[27] of the Division of Health Sciences and Technology served as a key bridging point among these individuals. Reflecting on his involvement on a 1985 "cut-patent"—a patent for which collaborator ties were *not* renewed or reinforced by subsequent patenting activity within the next five-year window—Cohen observed that nearly all of his collaborators on patents between 1985 and 1990 were graduate students from his lab who left the Boston region altogether on completing their degrees and research responsibilities at MIT. Their employment destinations included universities, hospitals, and, less frequently, businesses across the country and abroad. Cohen acknowledged that his particular division of MIT had not kept many of its own graduates, despite the fact that they often proved to be some of the most compelling candidates on the job market several years later (when they had become too senior and well compensated to be drawn back). Cohen's comments imply that elite universities might actually have less influence on local aggregation than non-elite universities, since their graduates are more likely to leave the area in search of comparably elite positions.

Nonetheless, based on his experiences at MIT and as the founder of Cambridge Heart, Inc., Cohen reported that because biotech information flows quite freely within the academic community, it is a particularly fertile environment for "proof of concept" research. Given that Boston technology relies to a much greater extent on university patents and published science, its technical social networks might actually be more connected than the Valley's. On the other hand, Cohen also believed that academic interest in new ideas tended to shift from the successful proof of one concept to another without sustaining the creation or exchange of knowledge through the subsequent design or development of commercial products. Compounding this problem, according to Cohen, the businesses that did bring such products to market inhibited any information flow specific to their commercialization processes.

Moreover, within the larger biotech industry, Cohen felt that the medical device business was quite distinct from the pharmaceutical business. The smaller end market for devices tended to sustain much smaller, less generously funded, and perhaps more insular companies. The smaller scale of medical device efforts is consistent with Froix's Valley experience, where he was able to commercialize breakthrough medical technology without the complete resources of a large firm. As a result of the typical transfer and development into smaller firms, we would expect less aggregation.

Patenting policies also influenced the second-largest connected component in Boston—composed largely of scientists and engineers at General Telephone and Electric (GTE)—during both the 1985–89 and 1986–90 windows. We asked GTE inventors Alfred Bellows and Jakob Maya[28] why the GTE component did not aggregate to rise in size rank from 1989 to 1990 and, more significantly, why it did not persist as the largest connected component after displacing the DEC component in 1991. They explained that people at GTE (and in the lighting technology field more broadly) typically view patents as very costly (for example, one quarter of a million dollars to internationally patent a single invention on an ongoing basis), so the culture of the industry is to limit them to genuinely innovative work for which the protection is thought absolutely necessary. Success in research on lighting technology has been carried out with and benefited from a high level of cross-fertilization between scientists in industry and academia (especially for government-contracted research and development). This work routinely generates papers, however, rather than patents.[29] Maya estimated, based on his own patent collaborator network graph from 1985–89, that the true size of his portfolio of collaborative relationships at the time was about three times what we had depicted, noting specifically that he had as many

[27] Richard Cohen (control to Radia Perlman) holds an M.D. and Ph.D. Dr. Cohen applies physics, mathematics, engineering, and computer science to problems in medicine and health. He helped found Cambridge Heart and is the Whitaker Professor in Biomedical Engineering at MIT.

[28] Alfred Bellows (control to Charles Kaufman) is currently working with OSRAM Opto Semiconductors. At GTE, Bellows was engaged in R&D projects relating to inorganic chemistry and the properties of materials such as ceramics and silicon nitride. Jakob Maya (control to Paul Koning) holds a Ph.D. and is currently leading research in lighting technology at Matsushita Electric Works R&D Lab. Before joining Matsushita, Maya was a director of R&D at GTE.

[29] Our patent data support this assertion. Patents also cite non-patent references, and these are mostly peer-reviewed scientific papers (Sorenson and Fleming 2004). Since 1975, Boston patents cited 30 percent more science papers on average than Valley patents did. Boston also had a greater proportion of academic patents over the entire time period as well.

papers with other authors (and at times not in the same firm) as he did patents. Second, the GTE component in Boston, already relatively weak, was probably made even weaker when GTE Sylvania sold its lighting business to Siemens's Osram in 1992, though this might have temporarily connected Siemens and GTE. Consistent with Froix's description of Raychem's implosion, Maya reported that people spent several years thereafter worried far more about simply keeping their jobs than about the quality, rate, or volume of their inventive work.[30]

The trade-offs between public science and private technology also influenced the collaborative linkages of Honeywell, the sixth largest connected component, though explicit career considerations also mattered. Thomas Joyce,[31] a lifetime employee at Honeywell (1960–2000), provided three reasons why the Honeywell component did not aggregate to rise in size rank from 1989 to 1990. (In fact, it dropped from fifth to sixth in the following year.) First, collaboration at Honeywell tended to be global rather than local; Joyce recalls working with a number of European Honeywell employees at the time but never exchanging information with anyone outside Honeywell, regardless of region. He attributed this fact partly to the nature of Honeywell's technology and partly to his own personal situation, as both his own skill set and Honeywell's development opportunities were constrained by the distinctly proprietary nature of the chip design work being done there.

Second, Joyce noted that he was linked to a comparatively more mature cohort of inventors, "older hangovers from the 1960s and 1970s," many of whom had more pressing family concerns or were nearing a reasonable age for retirement. Honeywell, like other Boston firms, made its pensions contingent on retirement with the firm, which certainly would have inhibited these older employees from leaving and thereby served as bridges to link the Honeywell component to other Route 128 components.[32]

Third, Joyce added that Honeywell's chip designers found themselves "under the secrecy cloak of Intel by the early 1990s"; collaborating with Intel prevented Honeywell from sharing knowledge elsewhere (publicly or otherwise). Our patent data strongly support Joyce's description of Honeywell's insularity. Of the eighty-one inventors in the 1986–90 window, eleven had collaborated on one or two of three non-Honeywell patents, while Honeywell held the ninety-one remaining patents linking this component.

Kaufman, Koning, and Perlman also emphasized how organizational culture influences the level of patenting, noting that DEC's explicit patenting policies motivated them to identify their patentable work proactively. They felt that these policies implicitly encouraged employees to identify other collaborators for each of their patents, partly because DEC awarded the full patent bonus amount of $500 to as many as three inventors per patent. So those with ideas to patent were often inclined to seek out collaborators (whether needed or not) in order to "share the wealth" and to encourage others to "return the favor." Additionally, DEC granted a steeper set of awards for cumulative patenting ($5,000 for 5 patents, $10,000 for 10, up to as much as $20,000 for 20, or perhaps even $25,000 for 25), and these awards allowed for any number of collaborators per patent. Kaufman also noted that DEC displayed a cyclical pattern based on patenting objectives that were established in response to a cross-licensing relationship with IBM, which would grant a company the use of all IBM-patented technologies in exchange for IBM's right to use that company's patented technologies. Because IBM's fee for this arrangement was inversely proportional to the size of the company's portfolio of patents, DEC business managers recognized a value to patents exceeding licensing revenue or protection from imitation.

It would seem that these policies would have increased collaborations and made the DEC component larger and more robust. Saxenian (1994) and others, however, have commented on the less collaborative norms within and across Boston firms. Paul Koning confirmed this reputation, describing how Ken Olsen, DEC's founder and CEO, routinely created competing internal groups as a means of fueling rapid progress. Koning went on to note that the practice severely strained internal morale and interdepartmental cooperation. Furthermore, given that patent law clearly stipulates that only contributing inventors be listed on a patent, the collaborative awards policy may have been of limited effectiveness. This might account for the persistent fragility in the DEC's networks and is consistent with its reputation for fostering competition between work groups.

[30] Maya left GTE just prior to this change because he anticipated it; he would have stayed otherwise.

[31] Thomas Joyce (control to Radia Perlman) worked as a logic designer and patented repeatedly at Honeywell, Honeywell Bull, and Bull until his retirement.

[32] Preliminary conversations with two Harvard Business School accounting professors, Paul Healy and Greg Miller, indicated great plausibility for this argument, although they were unaware of any specific citation in the accounting literature.

Taken collectively, these inventors' comments broadly suggest that the corporate policies and strategies of the dominant firms in the Boston region at the time often served to blunt aggregation both *within* and *across* firms. However, invention also stagnated at these firms due to more sweeping strategic business decisions—pursuing proprietary technologies (at DEC, Data General, and Honeywell) and selling ownership to an acquiring firm (at GTE and Honeywell). In the cases of proprietary technology, invention suffered as firms struggled with the negative economic outcome of their decision, while inventors were constrained in their careers by proprietary skill sets. In the cases of acquisition, it is reported that many inventors left their respective fields, retired, or focused more effort on keeping their jobs than on inventing. In the Valley, by contrast, inventors entered the external labor market with sellable skills because technologies were less proprietary (Angel 1989; Fallick et al. 2006).

At the same time, the slow pace of intra-organizational job movement was certainly not a function of limiting proprietary skill sets or organizational upheaval alone. The majority of Boston region inventors stressed firmly that their decision to remain in the same firms was primarily due to their satisfaction with both their work opportunities in those organizations and the way in which those organizations treated them as engineers and scientists. In fact, when these individuals finally left their firms (and any others subsequently in their careers), they reported that it was almost *always* because they saw no viable alternative; the organizations were either changing ownership or failing visibly. Naturally, many of these economic failures can be attributed in part to these firms' proprietary technological strategies. Thus there are two distinct ways in which the decision to remain with proprietary development hindered the growth of collaborative inventor networks in the Boston region. At the individual level, proprietary technology limited the job mobility of some, and at the organizational level, it contributed significantly to the ultimate failure or disruptive acquisition of at least three dominant firms in the area—DEC, Data General, and Honeywell.

DISCUSSION

As with all qualitative data, our presentation and analysis remain inseparable. Nonetheless, we wish to highlight three issues in our discussion. First, we are struck by the importance of institutions in the aggregation of regional inventor networks. Consistent with the themes of this volume, universities and postdoc programs play a catalytic role in the initial connections between components. This catalytic role creates opportunities for inventors (particularly young inventors) to forge bridging opportunities. Second, we are not struck by any fundamental differences in the network structures of Silicon Valley and Boston. To quantify these impressions, we explore and demonstrate that the micro-level structure of collaboration in the Valley is on average similar and sometimes less robust than that in Boston. Finally, we will collect our impressions of the differences between Boston and the Valley and comment on the Saxenian argument that the Valley is more networked.

IBM's postdoc program enabled young inventors to move across inventor components and explore new combinations of technologies and ideas. IBM modeled its program on Bell Lab's postdoc program (which, after the breakup of AT&T, no longer exists). When asked why IBM supported such a program, William Risk and John Campbell Scott provided a variety of reasons and motivations. First, the postdocs provided cheap labor. Second, new people with fresh ideas were seen as valuable. Third, IBM assumed that such people would depart as ambassadors for the firm. Risk and Scott did not mention the concerns about loss of proprietary information expressed by Hans Ribi and Pyare Khanna. Part of this reflects IBM's academic and admittedly "ivory tower" attitudes at the time. It also reflects founder and time period effects for the Almaden Lab in the 1960s. IBM operated as a virtual monopoly then. According to Scott, "the research division was set up by scientists with foresight." Their foresight had an impact well beyond IBM. (IBM has since reduced the postdoc program due to the firm's financial problems in the early 1990s. Other firms, however, such as Hewlett Packard, have begun similar programs [Fleming et al. 2005]).

The institutional support of mobility by young inventors appears to have greatly fostered their careers and, in turn, knowledge flow across firms in the Valley. Modeling at the inventor level of analysis also indicates that brokerage opportunities are most fruitful for young and relatively inexperienced inventors (Fleming, Mingo, and Chen 2007). After an inventor has gained a breadth of creative experience, she gains greater marginal benefits by collaborating cohesively because she brings non-redundant information that offsets the insularity of closed networks. It

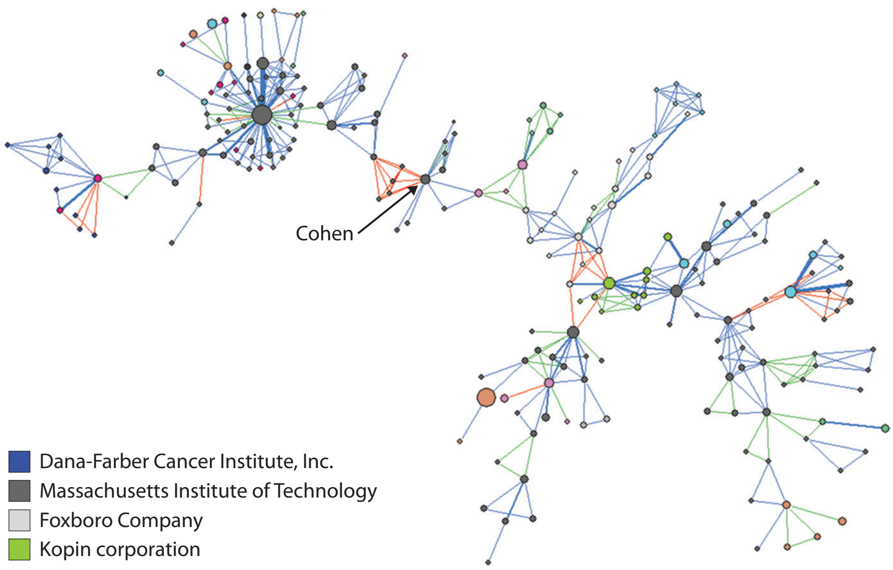

Figure 17.10 Boston's largest component in 1989, by assignee and importance of inventions. The MIT component did not aggregate into the 1990 largest component.

is interesting, though probably non-causal, that inventors are most mobile early in their careers, when they can most benefit from exposure to new ideas and technologies.

In the course of our interviews and graphical exploration of collaboration networks, we also perceived that Boston networks were less dense and robust than Valley networks. Whereas the IBM component emerged by 1987 to serve as the underlying foundation of the largest component in all subsequent years in the Valley, the composition of Boston's largest component continued to shift from one year to the next until 1993 when the Digital component was permanently displaced. Figure 17.10 illustrates another dramatic example of this process, the disintegration of the MIT/Foxboro/Dana-Farber component, Boston's largest component in 1985–89. Its red ties mark the patents that had expired by the following year (basically, patents that had been applied for in 1985). This illustrates how the component lost important bridging ties and completely fell apart. Given that this disintegration process would support the Saxenian arguments for Silicon Valley's more densely networked social structure, we tested the hypothesis that the Valley components were indeed more robust. Surprisingly, we found the opposite: paired comparisons across similarly ranked components indicate little difference, except that the second-largest component is more robust in Boston (GTE) than in the Valley (and, indeed, is by far the most robust of any component we analyzed). Appendix B describes the robustness analyses in detail. The analyses suggested that the Valley's greater degree of aggregation was not caused by a fundamental difference in the microsocial structure of its collaborative network. Indeed, the analyses (and even a visual comparison of the figures) indicated that the top six components of the two regions were quite similar, with the exception that the GTE/Siliconix component was more densely networked than its Valley counterpart.

Finally, we sought to understand whether Boston and the Valley had different information flows. We are struck by the bi-modal distribution of attitudes on the issue, mainly along professional lines and independent of the region. Most of the inventors from both regions expressed similar laissez-faire, open, and positive attitudes toward information flow. Many of their stories described an effort to evade efforts by management to contain their boundary-crossing collaborations. The most strident concerns about the leakage of proprietary information through collaborative relationships and extra-firm networks actually came from three Valley interviewees—Hans Ribi, Pyare Khanna, and (to a lesser extent) Salvador Umatoy.

Khanna explicitly described spillovers as bad, saying that it took one year to train a scientist, after which he preferred to keep the scientist in isolation. He felt that the important connections across the firm boundary were at his level and that scientists should work in silos. He sends his people to conferences, but only outside the Valley, to prevent poaching by rival Valley firms. At one time his firm had been in Concord, California, outside the traditional commuting distance of Silicon Valley. He preferred this location because salaries were 20–30 percent lower and people were less likely to leave. He remained noncommittal about why he subsequently moved his firm to Fremont (a city considered within the confines of the Valley), merely commenting: "Here there is the nucleus of growth." He opined that Kendall Square (a popular public plaza near MIT in Cambridge) in contrast, had no industry, only universities.[33] Khanna also remained noncommittal about the classic argument for location in technologically dynamic regions, namely the availability of technical personnel (Angel 1989).

The inventors in the Boston region noted a similar tension between managers and engineers regarding the decision to share information. "At Digital," Kaufman explained, "management thought we had all these great secrets to conceal; the engineers knew that the value was in collaboration." Koning felt that the core of the issue could be found in the underlying multiplicity of purposes for patenting. For example, an inventor might wish to patent a technology as a means to block its development by others in order to monopolize its sale or licensing. Alternatively, an inventor might patent as a means to steer the technology's subsequent development by others via "licensing on very generous terms" in order to acquire a first-mover/first-to-market advantage. (The latter motive is far more common for inventions that lend themselves to open standards and/or enjoy network effects, such as the computer networking hardware and software with which Koning is most familiar.) As both an engineer and an entrepreneur himself, Koning believed that in most cases, *both* motivations reflect the same basic principle: "You disclose x or license y because you make a business or engineering decision that the gain is greater than the loss." Naturally, this heuristic may not adequately address situations where business and engineering interests are at odds. Likewise, there is always a delicate balance between the desire to rely on public standards to protect proprietary decisions and the need to disclose proprietary decisions in order to institute those standards in the first place. As Koning put it, "It gets to be a very interesting dance. Sometimes it feels more like diplomacy than engineering."

Taken collectively, these inventors' comments suggest that simple characterizations of Boston secrecy and autarky versus Silicon Valley cooperation and interdependence fail to reflect the tension between managers and engineers on both coasts. Both communities struggled as they sought a practical and productive balance between making money, promoting public standards, and collectively solving problems. While unwanted spillovers certainly detract from the value of location in fast-paced technological regions like Boston and Silicon Valley, there are clearly many counterbalancing attractions. Managers can identify and attempt to keep their firm's mobile gatekeepers, but ultimately, and particularly in regions that do not enforce noncompetes or trade secret law, their options remain limited (Fleming and Marx 2006).

CONCLUSION

Why do regional inventor networks aggregate or disintegrate? And what influence does such aggregation have upon knowledge flows and creativity? We found many mechanisms that hamper aggregation, including the breakup of firms and the related uncertainty that saps morale and productivity; the dispersal of graduates to jobs outside the region; the departure of senior inventors to start-ups and self-employment rather than to other established firms; company policies that discourage collaboration; discrete product life cycles; and proprietary strategies that make collaboration unproductive. We found fewer influences that enhance aggregation. These include collaboration across academic and firm boundaries; collaboration within large firms; hiring local university graduates; and postdoc fellowships that seed local businesses with technically trained personnel. In the particular case at hand, Silicon Valley aggregated before Boston because Stanford graduates took employment at IBM's Almaden Valley Labs and because IBM sponsored a postdoctoral program that seeded the Valley with IBM patent coauthors. In contrast,

[33] An observation that is out-of-date, as any stroll through Kendall Square would reveal.

MIT graduates did not take employment at GTE, DEC, Data General, or Honeywell, and none of those firms sponsored collaborative programs like that at IBM. These differences were reflected in the generative ecologies of the two regions: Silicon Valley mobility increased the possibility of knowledge spillovers between firms and technologies. We found the attitudes of engineers toward spillovers to be remarkably similar in the two regions, however. Engineers appear eager to share ideas and facilitate creativity, independent of their location.

APPENDIX A: MATCHING ALGORITHM

We extracted source data on all granted U.S. patents from 1975 through 2002 from the United States Patent Office (USPTO) Cassis product, and MSA data for 2003 (ZIPList5 MSA 2003). Every patent includes all inventors' last names (with varying degrees of first and middle names or initials), inventors' hometowns, detailed information about the invention's technology in subclass references (there are over 100,000 subclasses), and the owner or assignee of the patent (generally a firm and less often a university, if not owned by the inventor). Since the USPTO indexes source data by patent number, we devised an inventor-matching algorithm to determine each inventor's patents and the other inventors with whom the focal inventor has coauthored at least one patent. The database includes 2,058,823 inventors and 2,862,967 patents (for description of more sophisticated algorithms and public accessible database, see Lai et al. 2011).

The matching algorithm refines previous approaches (Newman 2000). If last names match, first initials and middle initials (if present) must then match. Whole first names and whole middle names (if present) are then compared. If all these comparisons are positive, the algorithm then requires an additional non-name similarity: hometown and state, corporation (via assignee codes), or technology (via technology subclassifications). We also implemented a common name parameter that ignored the additional match requirement if the last name made up less than .05 percent of the U.S. population, as determined by the U.S. Census Bureau.

For 30 randomly selected inventors, the algorithm correctly assigned 215 of their 226 patents (as determined by résumé searches and personal contact). The 11 incorrectly determined patents were assigned to four isolated nodes (i.e., they did not create spurious cutpoints). Given the sensitivity of the measures to cutpoints, generating false negatives remains preferable to generating false positives or to incorrectly matching two different inventors.

The analyses presented relied on all patents with at least one inventor within the region. Thus if inventors from inside and outside a region coauthored a patent, the patent (and both inventors) would appear in each region. To explore the sensitivity of this definition, we regraphed all data with the more exclusive definition that did not include inventors from outside the region. While the graphs and network diagrams were generally smaller (as might be expected, since there will be at most the same number of inventors in each), the qualitative results were unchanged.

APPENDIX B: PATENT ROBUSTNESS ANALYSIS

One obvious explanation for the greater aggregation in the Silicon Valley network is that its components were more robust. We tested this hypothesis at the inventor level of analysis and then at the patent level of analysis. Figures 17.11 and 17.12 illustrate the inventor level of analysis for the largest and second largest components in the regions. (Illustrations for the third through sixth largest component comparisons looked qualitatively similar to those for the largest component and are not shown.) The y-axis of these illustrations is the proportion of nodes that remains connected in the largest resulting component after a proportion of the original nodes have been removed.The x-axis represents the proportion of original nodes that is removed.

Consider figure 17.12 first, illustrating the second largest components. The point 0.05 on the x-axis indicates that 5 percent of the nodes have been removed from what were originally the second largest components of Boston and the Valley. At this point, the y-axis indicates that the minimum proportion of nodes that remain connected in the reduced largest component is about 30 percent for the Valley and well over 40 percent for Boston. The graphed points are summary statistics (minimum, median, and maximum) of 50 samples for each data point. We sampled to avoid the combinatorial explosion of exhaustively calculating all possible choice combinations.

Figure 17.11 reveals very similar robustness for the two regions. Figure 17.12, however, illustrates that the Valley component is more

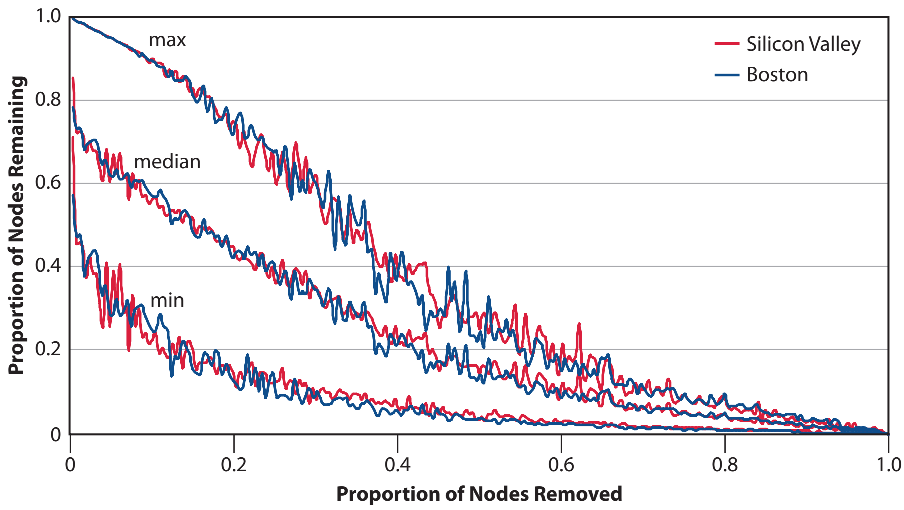

Figure 17.11 Size of component after removal of specified proportion of component's nodes, for Boston and Silicon Valley's largest components in 1989. The x-axis represents the proportion of original nodes that is removed. The y-axis illustrates the proportion of nodes that remains connected in the largest resulting component after a proportion of the original nodes have been removed.

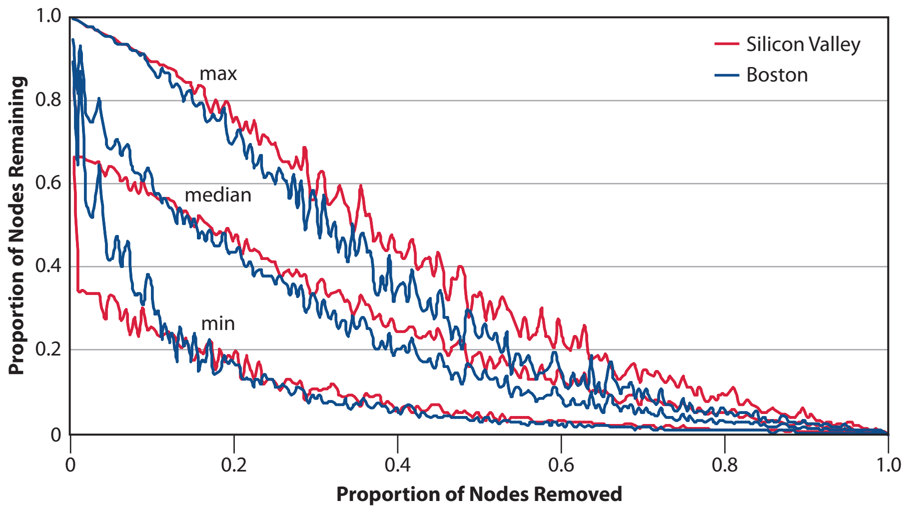

Figure 17.12 Size of component after removal of specified proportion of component's nodes, for Boston and Silicon Valley's second largest components. The x-axis represents the proportion of original nodes that is removed. The y-axis illustrates the proportion of nodes that remains connected in the largest resulting component after a proportion of the original nodes have been removed. As can be seen on the lower left, Silicon Valley was more vulnerable to node removal than Boston.

vulnerable to the loss of a few nodes. The steep initial drop in figure 17.12 for Silicon Valley indicates that the loss of a few key inventors quickly breaks the component up into much smaller pieces—similar to what is illustrated in figures 17.3 and 17.4. Silicon Valley appears to be simply more dynamic, breaking and re-forming nodes much more quickly, which is probably a reflection of its greater career mobility.

To confirm our results, we repeated the analysis at the patent level. For each of the components, we examine the extent to which the component would be disconnected by the removal of each patent. We define the extent to which a component is disconnected by the proportion of inventor dyads in that component that would no longer be able to reach one another after the patent is removed. We find this measure by considering each of these components individually and then calculating for each patent:

$$\sum_{c=1}^{K} (n/N)^2,$$

where N is the number of inventors in the original component, c is a component created by the removal of a patent, n is the number of inventors in a component c existing after a patent is removed, and K is the number of components in the post-removal network.

This measure yields a high value when the removal of a patent results in the creation of many new components and the inventors are divided equally among components. For example, if the removal of a patent divides a component into ten smaller components with one-tenth of the inventors in each component, this results in 0.9 of dyads being disconnected. However, if the removal of a patent results in a similar number of components but with inventors less evenly spread among them, the value generated by this measure will be smaller. For example, given a component of 100 inventors, if the removal of a patent breaks the component into 10 components with 9 of these being isolates and 91 inventors in the remaining component, then 0.171 of dyads are disconnected, indicating far less damage to the connectivity of the network. The maximum possible value would exist in a component where all inventors were coauthors on one patent and no other coauthorships existed. In this case the removal of the one shared patent would result in the disconnection of all inventor dyads.

We measure the vulnerability of each network by taking the mean proportion of inventor dyads disconnected by each patent. As stated earlier, the maximum value of this number is 1.0 for individual inventors. Calculating the maximum value for the mean of patents in a component is considerably more complex and beyond the scope of this chapter. However, since the maximum possible value will be related to the component size, caution should be exercised when comparing mean values across components of different sizes.

Table 17.2 illustrates robustness results. As the low numbers suggest, most patents within each component can do only minimal damage to the network. What is most striking is the lack of systematic difference across the two regions. The mean vulnerability over all the Boston components is 0.0241; over all Silicon Valley components it is 0.0272. Consistent with the inventor-level analysis, the second component appears to be much more robust in Boston, relative to all other components in both Boston and the Valley.

Both of these analyses suggest that the Valley's aggregation did not occur because its components were more robust and able to merge with other components.

Table 17.2.
Patent Analysis of Component Robustness

Component	Component Vulnerability	No. of Patents	Maximum
Boston 1	.0212 (.0763)	208	.52
Boston 2	.0074 (.0231)	345	.20
Boston 3	.0301 (.0762)	123	.49
Boston 4	.0179 (.0806)	182	.65
Boston 5	.0226 (.0610)	116	.35
Boston 6	.0451 (.0989)	45	.46
Silicon Valley 1	.0311 (.0757)	159	.49
Silicon Valley 2	.0208 (.0552)	161	.45
Silicon Valley 3	.0209 (.0477)	107	.38
Silicon Valley 4	.0330 (.0950)	131	.52
Silicon Valley 5	.0338 (.0729)	60	.49
Silicon Valley 6	.0237 (.0712)	78	.54

Note: Component vulnerability is the mean number of the proportion of inventor dyads disconnected by the removal of each patent within a given component (higher values indicate more vulnerable components). Standard deviations in parentheses.

REFERENCES

Albert, M. B., F. Narin, D. Avery, and P. McAllister. 1991. "Direct Validation of Citation Counts as Indicators of Industrially Important Patents." *Research Policy* 20:251–59.

Almeida, P., and B. Kogut. 1999. "Localization of Knowledge and the Mobility of Engineers in Regional Networks." *Management Science* 45:905–16.

Angel, D. 1989. "The Labor Market for Engineers in the U.S. Semiconductor Industry." *Economic Geography* 65(2):99–112.

Angel, D., and J. Engstrom. 1995. "Manufacturing Systems, and Technological Change: The U.S. Personal Computer Industry." *Economic Geography* 71(1):79–102.

Batagelj, V. and A. P. Mrvar. 1998. "A Program for Large Network Analysis." *Connections* 21:47–57. Pajek version 0.91, 2003, http://vlado.fmf.uni-lj.si/pub/networks/pajek/.

Beam, A. 1989. "Our Technology Graveyard." *Boston Globe*, July 26, p. 21.

Burt, R. 1992. *Structural Holes*. Cambridge, MA: Harvard University Press.

Clark, D. 1991. "Newcomers Put Stamp on Silicon Valley." *San Francisco Chronicle*, July 8, p. B1.

Cohen, F. 2003. Personal interview. February 13, Natick, MA.

Cohen, W., and D. Levinthal. 1990. "Absorptive Capacity: A New Perspective on Learning and Innovation." *Administrative Science Quarterly* 35:128–52.

Fallick, B., C. Fleischman, and J. Rebitzer. 2006. "Job-Hopping in Silicon Valley: Some Evidence Concerning the Micro-Foundations of a High Technology Cluster." *Review of Economics and Statistics* 88:472–81.

Feldman, M. 2001. "The Entrepreneurial Event Revisited: Firm Formation in a Regional Context." *Industrial and Corporate Change* 10(4):861–92.

Fleming, L. 2001. "Recombinant Uncertainty in Technological Search." *Management Science* 47(1):117–32.

Fleming, L., and K. Frenken. 2006. "The Evolution of Inventor Networks in the Silicon Valley and Boston Regions." *Advances in Complex Systems* 10(1): 53–71.

Fleming, L., and M. Marx. 2006. "Managing Creativity in a Small World." *California Management Review* 48:6–27.

Fleming, L., D. Chen, and S. Mingo. 2007. "Collaborative Brokerage, Generative Creativity, and Creative Success." *Administration Science Quarterly* 52:443–75.

Fleming, L., C. King, and A. Juda. 2007. "Small Worlds and Regional Innovation." *Organization Science* 18(2):938–54.

Fleming, L., M. Thursby, and J. Quinn. 2005. "HP Nanotech: Partnership with CNSI." Harvard Business School case 606-045. http://hbr.org/product/hp-nanotech-partnership-with-cnsi/an/606045-PDF-ENG.

Florida, R., and M. Kenney. 1990. *The Breakthrough Illusion*. New York: Basic Books.

Gilson, R. 1999. "The Legal Infrastructure of High Technology Industrial Districts: Silicon Valley, Route 128, and Covenants Not to Compete." *New York University Law Review* 74(3):575–629.

Glaeser, E., H. Kallal, J. Scheinkman, and A. Shleifer. 1992. "Growth in Cities." *Journal of Political Economy* 100(6):1126–53.

Graham, R. 1989. "'Miracle' Proves a Mirage: New Arrivals Find Too Little of High-Tech Boom, Too Late." *Boston Globe*, July 28, p. 13.

Granovetter, M. 1973. "The Strength of Weak Ties." *American Journal of Sociology* 78:1360–80.

Grove, A. 1990. "The Future of the Computer Industry." *California Management Review* 33(1):148–61.

Gulati, R., and M. Gargiulo. 1999. "Where Do Interorganizational Networks Come From?" *American Journal of Sociology* 104(5):1439–93.

Gura, T. 2004. "Joining a Trend, Scientists Increasingly Say 'Call My Agent.'" *Science* 303:303–5.

Henderson, V. 1997. "Externalities and Industrial Development." *Journal of Urban Economics* 42: 449–70.

Henderson, V., A. Kuncoro, and M. Turner. 1995. "Industrial Development in Cities." *Journal of Political Economy* 103(5):1067–90.

Jacobs, J. 1970. *The Economy of Cities*. New York: Random House.

Kenney, M., and U. von Burg. 1999. "Technology, Entrepreneurship, and Path Dependence: Industrial Clustering in Silicon Valley and Route 128." *Industrial and Corporate Change* 8:67–103.

Krugman, P. 1991. "Increasing Returns and Economic Geography." *Journal of Political Economy* 99(3):483–99.

Lai, R., A. D'Amour, A. Yu, Y. Sun, and V. Torvik. 2011. "Disambiguation and Co-author Networks of the U.S. Patent Inventor Database." Working paper, Harvard Business School.

Leslie, S., and R. Kargon. 1996. "Selling Silicon Valley: Frederick Terman's Model for Regional Advantage." *Business History Review* 70:435–72.

Marshall, A. 1920. *Principles of Economics*. 8th ed. London: Macmillan.

Marx, M., J. Singh, and L. Fleming. 2011. "Regional Disadvantage: Non-Competes and Brain Drain." Working paper, MIT Sloan School of Management.

Marx, M., D. Strumsky, and L. Fleming. 2009. "Mobility, Skills, and the Michigan Non-Compete Experiment." *Management Science* 55:875–89.

McCormick, J. 1999. "Asia's Best and Brightest Flock to Silicon Valley." *Electronic Business*, http://www.reed-electronics.com/eb-mag/index.asp?layout=article&articleid=CA65539&rid=0&rme=0&cfd=1.

Mowery, David C., Richard R. Nelson, Bhaven N. Sampat, and Arvids A. Ziedonis. 2001. "The Growth of Patenting and Licensing by U.S. Universities: An Assessment of the Effects of the Bayh-Dole Act of 1980." *Research Policy* 30(1):99–119.

Newman, M. 2000. "The Structure of Scientific Collaboration Networks." *Proceedings of the National Academy of Sciences of the United States of America* 98:404–9.
Nohria, N. 1992. "Information and Search in the Creation of New Business Ventures: The Case of the 128 Venture Group." In *Networks and Organizations: Structure, Form, and Action*, ed. N. Nohria and R. Eccles. Boston: Harvard Business School Press.
Owen-Smith, J., and W. Powell. 2004. "Knowledge Networks as Channels and Conduits: The Effects of Spillovers in the Boston Biotechnology Community." *Organization Science* 15(1):5–21.
Packard, D. 1995. *The HP Way: How Bill Hewlett and I Built Our Company*. New York: HarperCollins.
Piore, M., and C. Sabel. 1984. *The Second Industrial Divide: Possibilities for Prosperity*. New York: Basic Books.
Robertson, P., and R. Langlois. 1995. *Firms, Markets, and Economic Change: A Dynamic Theory of Business Institutions*. New York: Routledge.
Rosegrant, S., and D. Lampe. 1992. *Route 128: Lessons from Boston's High-Tech Community*, New York: Basic Books.
Saxenian, A. 1990. "Regional Networks and the Resurgence of Silicon Valley." *California Management Review* 33(1):89–113.
———. 1994. *Regional Advantage: Culture and Competition in Silicon Valley and Route 128*. Cambridge, MA: Harvard University Press.
———. 1999. "Comment on Kenney and von Burg, 'Technology, Entrepreneurship, and Path Dependence: Industrial Clustering in Silicon Valley and Route 128.'" *Industrial and Corporate Change* 8:105–10.
Schweikart, L. 2000. *The Entrepreneurial Adventure: A History of Business in the United States*. Fort Worth, TX: Harcourt College Publishers.
Simon, J. 1989. "Job Chill on 128: With Cutbacks and Slowed Growth, the Hiring Sizzle Is Gone." *Boston Globe*, April 30, p. A1.
Singh, J. 2005. "Collaborative Networks as Determinants of Knowledge Diffusion Patterns." *Management Science* 51(5):756–70.
Sorenson, O., and L. Fleming. 2004. "Science and the Diffusion of Knowledge." *Research Policy* 33(10): 1615–34.
Stein, C. 1989a. "128: Why It Will Never Be the Same." *Boston Globe*, January 3, p. 21.
———. 1989b. "Along Route 128, High Tech Hits Lows." *Boston Globe*, August 1, p. 1.
Stern, S., and M. Porter. 2001. "Innovation: Location Matters." *Sloan Management Review* 42(4).
Stewart, R. 2004. Personal interview, June 17, Cambridge, MA.
Watts, D., and S. Strogatz. 1998. "Collective Dynamics of Small-World Networks." *Nature* 393:440–42.
ZIPList5 MSA. 2003. Downloaded April 24 from CD Light, LLC: http://www.zipinfo.com/products/z5msa/z5msa.htm.