Why the Valley Went First: Agglomeration and Emergence in Regional Inventor Networks

Lee Fleming
Morgan Hall T95
Harvard Business School
Boston, Ma.
lfleming@hbs.edu
(617) 495-6613

Lyra Colfer
lcolfer@hbs.edu

Alexandra Marin
amarin@wjh.harvard.edu

Jonathan McPhie
jmcphie@fas.harvard.edu

Feb. 15, 2003

Acknowledgements: We thank 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 importantly, we would like to thank all the inventors who spent a great deal of time with us discussing their careers.

Abstract: Are the inventor networks of Silicon Valley more densely connected than those of the Boston Route 128 corridor? The evidence remains mostly historical and controversial to date. We develop an analysis of all the patented inventors in both regions since 1975 and find that the networks of Silicon Valley are simultaneously more connected *and* less robust than those of Boston. Of greatest interest, Silicon Valley demonstrates a dramatic agglomeration of its inventors, such that half of them can trace an indirect path to one another through co-authors by 1999. Boston, despite a very similar number of patents, inventors, technologies, firms, and overall density of ties, agglomerates later and even today lags Silicon Valley. This process of emergence of a "giant component" occurs through the linking of a region's larger components. Based upon interviews with inventors who did and did not create linking ties across a region's components, we identify a variety of similarities and differences in the agglomeration and non-agglomeration processes of co-authoring networks across the two regions. While our limited sample found more reports of information flow across firms in the Valley, inventors reported very similar experiences and attitudes in the two regions. Ultimately, we find an institutional explanation for a large portion of the Valley's advantage: a single post-doctoral fellowship program at IBM's Almaden Valley Labs was responsible for up to 30% of the region's initial agglomeration process.

Introduction

The news heralded in the Boston Globe throughout 1989 did not bode well for innovation at firms along the high-tech corridor of Route 128 in Massachusetts. While many of their counterparts in California's Silicon Valley were still faring quite well, several of the region's largest firms (including Digital Equipment, Data General, Wang, Prime, Lotus Development, Cullinet Software, and even Polaroid) were facing worsening earnings and imminent layoffs. After creating more jobs in the first half of that decade than peers and rivals across the entire nation, firms along Route 128 were experiencing an ominous economic reversal. From a peak of 261,000 in 1984, their collective employment fell steadily through 1990, dropping more than 50,000 jobs to roughly where it had stood at the start of the decade; this drop reflected an 11% loss, compared with a nationwide decline of just 4% during the same time-frame (Stein 1989a; Saxenian 1994). In contrast to the Route 128 experience, high tech firms in other regions fared quite well during the time period. Companies like Sun Microsystems and Apple in Silicon Valley had "positively exploded," as did Compaq in central Texas and Microsoft in Washington (Stein 1989b). Silicon Valley, in particular, saw the market value of its firms jump $25 billion between 1986 and 1990, while the collective valuation of firms along Route 128 increased by just $1 billion during that time (Schweikart 2000).

A handful of theories are commonly offered to explain this noteworthy regional divergence in economic performance, typically with special attention to the comparatively strong performance of Silicon Valley relative to Route 128. Prior analyses of one or both of these regions have emphasized the relative importance of a multiplicity of conceptually distinct but practically overlapping factors, including labor mobility and entrepreneurship and constraints on both (Angel 1989; Gilson 1999; Saxenian 1994); business culture and organizational form (Saxenian 1994); the availability of venture capital (Saxenian 1994) and institutions to nurture new firm formation more generally (Kenney and von Burg 1999); university involvement (Leslie and Kargon 1996); the path dependence of technological development (Kenney and von Burg 1999); and demographic diversity (Clark 1991, McCormick 1999).

The broader literature on economic development typically refers to "external economies" and "agglomeration economies" as a means to explain the comparative advantage that firms can gain from their regional location. [1] Krugman (1991) notes that the economic literature typically affords three explicit reasons for regional localization: a proximate pool of technically skilled workers, a local supply of specialized inputs including both goods and services, and an ongoing knowledge spillover across firms and other organizations within that region. By this description, both Silicon Valley and Route 128 clearly appear to be textbook examples of agglomeration economies or, more specifically, "cumulatively self-reinforcing agglomerations of technical skill, venture capital, specialized suppliers, and services, infrastructure, and spillovers of knowledge associated with proximity to universities and informal information flows" (Saxenian, 1994). As Saxenian (1994) observes, however, this description does not adequately address why economic agglomeration economies ultimately produced a more permanent and self-reinforcing dynamic of growth in Silicon Valley than along Route 128.

When the divergence in performance across these two regions first became evident in the late 1980s, industry observers and journalists largely fell into two broad camps: those who saw a story about technological trajectories and those who saw a story about divergent east coast/west coast business mentalities. The former tended to characterize the coinciding success of Silicon Valley and failure of Route 128 as two faces of the very same coin – that is, a single dominant trend towards low cost personal computing. Where Silicon Valley firms like Apple, HP, and Sun were capturing the upside of this trend by initiating the early development and sale of workstations and personal computers, their products were actually supplanting those of the minicomputer manufacturers that dominated Route 128. While the latter camp acknowledged the prima facie truth in this explanation, its proponents argued that it was incomplete insofar as this technological divergence was itself the consequence of fundamental differences in the two regions' underlying business cultures. Put simply, conventional wisdom at the time held that "Boston-area executives in their button-down shirts and brown shoes are more cautious

[1] We restrict our usage of the term "agglomeration" to refer to the linking of previously separated inventor networks into larger networks and the term "non-agglomeration" to refer to mechanisms that retard such linking or split previously connected networks.

and slow-moving than their California rivals in polo shirts and Reeboks." (San Jose Mercury News 1989)

Scholars have elaborated a handful of variants on these two basic viewpoints. The first viewpoint is most often associated with Saxenian (1990, 1994) and presents Silicon Valley as a cooperative industrial system. Saxenian offers historical and anecdotal evidence in her 1994 publication to support the view that Silicon Valley's norms of rapid labor mobility, collective learning, inter-firm dependence, and informal exchange gave it a decisive edge in competing against the more conservative, secretive, risk averse, and autarkic firms of Route 128. Among these divergent norms, Angel (1989) presents evidence which underscores the particular importance of rapid labor mobility, while Gilson (1999) complements the role of informal mobility norms by asserting a role for formally enforced legal rules, such as non-disclosure and non-compete covenants, which he finds were enforced along Route 128 but not in Silicon Valley. Almeida and Kogut (1999) sampled important patented inventors and found greater mobility amongst Silicon Valley professionals.

The second viewpoint is most often associated with Florida and Kenney (1990), who contend that a cultural or normative explanation is incomplete and inaccurate. They counter that business in Silicon Valley throughout the 1980s was not driven by a spirit of cooperation but rather by "the rule of profit." They emphasize the degree to which intense, increasingly global competition drove both regions to behave more similarly than differently, portraying their common business practices as downright "Hobbesian" in nature (see Florida and Kenney 1990, pgs. 98-118). Moreover, Kenney and von Burg (1999) propose that any divergence between the two regions' organizational processes, forms, or networks was ultimately less important than differences in their respective technological competencies (that is, semiconductors in Silicon Valley, vs. minicomputers along Route 128) and in their institutions for new firm formation. Building upon the finding of Robertson and Langlois (1995) that product cycle stage influences industrial organization, Kenney and von Burg 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. Nohria (1992) provides a counter-example to the perception that only Silicon Valley has effective networking institutions, with his description of the 128 Venture Group breakfast meetings.

The evidence and research methodologies to date remain largely historical on both sides of the debate. We add to the discussion by focusing upon the patented inventor co-authorship networks of the two regions. Following Fleming, King, and Juda (2003, see figure 1), we demonstrate that the largest connected network component in Silicon Valley underwent a dramatic transition in the early 1990s. Starting from a small and similar size to that of Boston's largest connected component in 1989, it grew rapidly from 1990 forward to encompass almost half of Silicon Valley's patenting inventors by 1999. In marked contrast, 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. This phenomenon merits study because Fleming, King, and Juda (2003) demonstrate a significant correlation between agglomeration and subsequent inventive productivity in the region. They argue that greater connectedness enables greater knowledge spillovers and more productive inventive search within a region, an argument that is bolstered by Singh's (2003) evidence that future prior art citations are more likely to occur within connected, as opposed to isolated, networks.

We investigated this divergence more closely by focusing on the actual ties that inventors created – or failed to create – across key network components within these two regions. We first illustrate how inventors consistently bridged larger network components in Silicon Valley, and thereby drove the runaway growth of its largest connected network component over time. We then report observations from the actual creators of those bridging ties, as well as similar "counterfactual" inventors who did not create such ties across similarly sized network components in the two regions. Based on these interviews, we find that inventors created bridging ties for a broad range of reasons, including movement into local industry upon graduation from doctoral programs, movement from industrial post-doctoral fellowships to new employers, and crossfunctional collaboration between distinct departments or working groups within established firms. Inventors failed to create ties for an even greater variety of reasons, including the strength of internal labor markets and employee loyalty, the preference of key inventors at established firms to move to start-ups or self-employment (rather than other established firms), the low hiring and departure rates found at some established firms as a consequence of economic downturn, the dispersal of graduates to non-local employment, the counterproductive impact of internal competition, and corporate expense controls that discouraged patenting due to the high cost of filing. We compliment these interviews with analyses of the robustness of patent and inventor networks, and descriptive statistics for alternative explanations of the agglomeration processes.

By focusing on a particular time period and social network, we can detail a more nuanced story than the discussions to date. Silicon Valley's patenting co-authorship networks are indeed more connected, but less robustly, than Boston. Information flow between firms might have been richer in the Valley, but there were plenty of engineers and scientists in Boston that were also willing to risk management stricture and talk to their colleagues across organizational boundaries. Ultimately, we find that a single institutional program, namely the post-doc fellowship program at IBM's Almaden Valley Labs, was responsible for up to 30% of the Valley's initial agglomeration. Without this single program, the Valley's claim to more densely connected social networks becomes much more tenuous.

Documenting the Emergence of the Giant Component

To gain empirical traction on the contentious issue of differences in the social structure of Boston and Silicon Valley, we consider all patented inventors and their co-authorship relations in the two regions. Basically, a relationship exists between patented inventors if they have co-authored 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 generally demonstrate a skewed count 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" (other literature sometimes uses the abbreviation "LC").

Figure 1 illustrates the proportion of patented inventors encompassed within a region's largest component. [2] For example, if there were 10 inventors in a region, and six of them co-authored any patents together in the prior five years, then the proportion in that region would be 0.6. If four had co-authored patents, and no other group of co-authors was bigger, then the proportion would be 0.4. 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 co-authorship to one another and lie within the same component. The interesting feature of figure 1 – and first motivation for this paper – is the agglomeration process in Silicon Valley that began in 1990 and culminated in almost 50% of the Valley's inventors agglomerating into the largest component by 1998. Boston, by contrast, did not begin this process until 1995, and its largest component had only reached 25% by 1998.

We begin by illustrating the smaller component agglomerations that caused the diverging upturns in Figure 1. The histograms of Figure 2 show which of the prior year's network

---

[2] We define a patent as being in a region if at least one inventor lives within that region, as determined by their 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 a regional inventor, if they worked with someone who lived within the region. We discuss this issue at length below and illustrate a more restricted definition (exclusively Boston residents in the 1120 MSA or Santa Clara residents in the 7400 MSA) in figure A13. As can be seen in figure A13, the qualitative differences in the processes remain very similar. All figures include all 337 U.S. MSA regions for comparison and assume five-year moving windows.

components agglomerated 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, and each region contains more than 2000 such components of varying sizes in any given year (most of which contain just 20 or fewer inventors, and therefore fall above the frequency cutoff used for the y axes in the graphs below).

Figure 3 illustrates the early similarity in the distributions of the two regions' components.[3] In 1988, Boston had a larger largest component (although Figure 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 approximately similar. Yet, as the 1989 panels 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 merged to form its largest component in 1990. This difference in agglomeration processes continues in following years such that, by 1992, the largest component in Silicon Valley had over 1600 inventors, in contrast to Boston's approximately 330 inventors. Furthermore, Figure 3 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 immediately following time window.

[3] 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.

Fieldwork

We conducted in-depth interviews with key inventors in both regions to understand the historical and social mechanics of the agglomeration process. We identified these inventors in two rounds. First, we graphed the largest component of 1990 in both regions to pinpoint the inventors that provided crucial linkages from the previous year's components. For example, drawing on the histograms above, we identified 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 inventors who 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 "counterfactual" inventors based on its similarity to the first set of linking inventors. All inventors from similarly sized components in the region that did not agglomerate into the 1990 largest component were at risk of counterfactual 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 number of patents by time period (or basic inventive productivity), future prior art citations by time period (since citations have been shown to correlate with patent importance, see Albert et al. 1991), mean degree of collaborations, and clustering of the inventor's collaborators (similar to the Burt (1992) measure of constraint, or the degree to which your immediate alters have non-redundant information, measured as the number of ties between your alters).

We were able to contact many of the linking and counterfactual inventors we identified. We interviewed them during July and August of 2003, presenting each inventor with the histograms described here and an illustration of their own network component with all of their co-authors identified. We asked them about their careers, what was happening within their component during the time period (especially with regards to job mobility), and where their collaborators were now. We asked specifically about the collaborators in their patent networks and also about any other networks such as social or scientific networks. Follow-up questions probed for inaccuracies in our illustrations and name-matching algorithm, as well as sampling bias caused by failed patent attempts or 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 co-authors accurately (for example, Salvador Umatoy indicated a failed project had not been patented, but that his collaborators were all reflected on other successful patents; Jakob Maya noted similarly that some of his projects concluded with published papers rather than patents, as did Radia Perlman and Charles Kaufman, but none recalled any patent collaborators who were not represented in his network component as illustrated). Given evidence from patent citation data that information flows across these indirect linkages (Singh 2003) and that agglomeration processes improve regional inventive productivity (Fleming, King, and Juda 2003), we also asked them about information flow across the illustrated linkages. Finally, we simply asked them what they thought might cause the agglomeration processes we observed.

Qualitative data

Our interviews with the regions' inventors revealed common and specific reasons for agglomeration and non-agglomeration. These reasons are summarized in table 1. We did not hear of any exactly similar agglomeration processes, although we will discuss the obvious similarities of the different stories below. The Silicon Valley specific reasons for agglomeration included an IBM post doc program and local hiring of local graduates. Boston specific reasons included internal collaboration within Digital Equipment Corporation. Common non-agglomeration reasons between the regions included big firm instability, internal labor markets, and personnel movement to start-ups. Valley specific reasons for non-agglomeration included personnel movement to self-employment, and Boston specific reasons included non-local graduate employment, lack of internal collaboration, internal firm collaboration that was non-local, and patenting policies.

Valley specific reasons for agglomeration

One firm drove both agglomeration processes we identified in the Valley. Silicon Valley components merged because IBM hired local doctoral students, and because it sponsored a post-doctoral fellowship program. The first process connected Stanford components with IBM, and the latter process connected IBM to the large pharmaceutical and biotech component in the Valley. Figures A1 and A2 illustrate the largest component of the Valley in the 1986-1990 time period. A1 colors the nodes by firm and A2 colors them by the previous period's subcomponent [4].

IBM's Almaden Valley Research Lab provided the stable backbone of the 1990 Silicon Valley agglomeration. IBM constituted the largest component in the Valley by 1987 and continued as the largest component in 1988 and 1989 (in contrast to the unstable backbone of the Boston agglomeration process, a point to which we will return later). Stanford's Ginzton Applied Physics Lab network joined the Valley's largest component in 1989 when William Risk graduated, accepted employment at IBM, and linked Professor Gordon Kino and his students to the Almaden Lab component. Further Stanford agglomeration occurred in 1990 with William Kozlovsky's graduation and departure from Prof. Robert Byer's lab. The most interesting and largest agglomeration occurred, however, with the linkage of the second largest component in the Valley with IBM in 1986-1990. Surprisingly, the second largest component consisted of Syntex (arguably a research intensive pharmaceutical firm) and smaller biotech firms. The actual connection occurred through the (now failed) startup of Biocircuits.

Campbell Scott attributed the agglomeration of the biotech component to a unique post-doc program run by IBM. The Almaden Lab hired post-docs 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

[4] All network diagrams were plotted in Pajek with a directed force algorithm (Batagelj and Mrvar 1998). Each node corresponds to an inventor and network ties correspond to co-authorship of at least one patent. Node size 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). Tie strength corresponds to co-authorship strength, as measured by the number of co-authored patents, normalized by the number of inventors on the patents.

and similar programs at Bell Labs, the practice intended to seed the technological community with more 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 startups (which does not create ties between large components), the post-docs found future employment across a variety of firms. Hence, the IBM post-doc program played a crucial role in the initial and continuing agglomeration processes in the Valley, because it linked large components to other large components.

While the connection of the Syntex and IBM components relied upon the post-doc program, the connections occurred indirectly through Biocircuits, an early electronics-biotech (and ultimately failed) startup that developed biosensors. [5] Todd Guion, a Stanford graduate in chemistry, worked for Campbell Scott during his post-doc at IBM, and then left to take 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, the CEO of Biocircuits, to contact Scott for help. Scott had initial difficulty but succeeded in securing permission from IBM management to act as a scientific advisor, 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, however, the prominent pharmaceutical inventor on the other side of the Biocircuits bridge.

[5] It might be described as an early forerunner of today's combinations of biological and digital technologies, as reflected by products such as Affymatrix's combination of assay and semiconductor technology into a gene array chip, publications such as BIO IT World that focus on the application of computing power to biological and genomic problems, and research laboratories such as Stanford's BIO-X that hopes 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. Only now are some firms (such as Affymatrix) beginning to make money.

Hans Ribi, the owner of Biocircuits and a Stanford graduate in biochemistry, had a much less positive view of information flow across collaborative linkages (believing that it should not and generally doesn't occur). He argued that patents are used to protect proprietary property and that co-authorship did not indicate a higher probability of information flow (he was not aware of Singh's 2003 evience). Interestingly, 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 startups at the time of the interview and felt much more vulnerable to the loss of proprietary information and key individuals, as opposed to the resignation and good corporate citizen attitude of IBM scientists. This reaction from the biotech/pharma managers also raises the possibility that the norms of information exchange are industry *and* location specific – perhaps the anecdotes of Silicon Valley's openness are only pertinent to computer hardware. This is idiosyncratic to the Valley, because - and corroborating Saxenian's (1994) arguments - we also found that managers of Boston hardware firms did not view information spillovers favorably.

Returning to the Stanford-IBM connections, William Risk and Professor Gordon Kino described a much more conventional linkage process, namely, the movement of graduate students from university labs to private firms.[6] Kino reported that his students of the era had gone on to a variety of academic and technical positions, for example, Tektronix and then a small start up in Oregon, Bell Labs, AT&T, IBM New York, a start up in the Valley, self employment as an entrepreneur in Wyoming, and academic positions at Stanford, UC Santa Barbara, and Wisconsin. 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, electronic, optics, and scientific instrumentation. Professor Kino's description of local employment sounds exactly opposite to Professor Cohen's description of his students' non-local employment below. As such, the processes of local and non-local employment of graduates surely operate

[6] Technically, the agglomeration between Gordon Kino of Stanford and William Risk of IBM occurred one year earlier than the 1986-1990 window. Given that we were unable to meet with William Kozlovsky and Robert Byer by the time of submission and given that the Stanford-IBM inventors knew each other well and corroborated the processes described here via phone interviews, we report from Kino and Risk.

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. Categorizing these processes as Silicon Valley specific is therefore merely an expositional convenience, based upon our interview sampling and the economic conditions at the time.

Consistent with our observation of Stanford-IBM ties, 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. Kino and Risk renew old ties mainly at conferences, although students also visit their former advisors at school (Risk had done so the week prior to the 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, informal social network. In particular, they felt that graduates from the Ginzton Applied Physics Lab at Stanford had maintained a particularly close contact since leaving Stanford.

Boston specific reasons for agglomeration

Boston's largest component in 1990 resulted from internal collaboration within Digital Equipment Corporation. Illustrated in figure A7 and A8, the internal agglomeration occurred in response to newly initiated interaction of multiple smaller work groups within DEC at that time. Discussing his own role as a "point of connection" in these processes, Charles Kaufman 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" identified from four distinct working groups in order to design DEC's "next generation of security." Second, he noted that while he was a software engineer by trade, he often socialized with those working in hardware. In addressing the same question, Paul Koning spoke more directly to his participation on individual patents, noting 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 actively sought brainstorming solutions from engineers on a routine basis. Second, he mentioned that 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 in instances where its participants spanned company boundaries. Both Kaufman and Perlman independently confirmed this viewpoint, enumerating several bureaucratic obstacles they have had to surmount 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.[7] Like Campbell Scott in the Valley, these Boston inventors overcame legal and bureaucratic obstacles to collaboration across boundaries.

Koning and Kaufman both reported switching job functions within DEC several times [8], 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 for new ones. Kaufman found that he usually maintained links to these individuals by passing back old information relating to his prior work, rather than by applying that same information to his new work going forward. On the other hand, however, he also noted that he and Perlman are a significant exception to this trend because they have continued to collaborate in new ways (for example, on multiple academic papers and publications) for well over a decade now, despite working for different employers since 1993, when Kaufman left DEC for a local position at Iris

[7] This joint invention was a strong password protocol that 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 share the protocol publicly.

[8] Koning reported switching firms several times (choosing one start-up after another, including two of his own founding – clearly not the clichéd risk-averse and conservative Boston inventor).

Associates (a small, high risk software firm in the same region), and Perlman left DEC for a local (but telecommuting) position with Novell.[9]

Common reasons for non-agglomeration

We heard a number of common explanations for non-agglomeration between components across the regions. First, large established firms with internal labor markets generally retain their employees. Second, successful inventors from established firms generally go to startups, instead of other large established firms. This movement implies that they will link established firms with large components to start-up firms with small or non-existent components, rather than large components to large components. Finally, when established firms become unstable, they will not hire and their current inventors will often spend more time covering their political exposure or looking for a new job, rather than inventing.

Applied Materials (the 4th largest component in the Valley) did not agglomerate into the largest component for a variety of reasons. Its business boomed during the era and there existed many internal technical and managerial opportunities for its employees. It retains (even during much tougher times more recently) a strong internal labor market and hires mostly new college graduates. During the time period of study, the firm provided its employees with generous incentives, such as stock options, to stay within the firm. Most of the colleagues in Salvador Umatoy's network (figure A5) had remained within the firm and were now either managing at senior levels or still contributing technically (they were literally close, "he works down that aisle…he works in the building next door"). He commented that only managers went to other large firms – in contrast, senior engineers went to startups. When asked about people in his network with whom he had not patented at the time and 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 that left for IBM. Umatoy did not work directly with this manager (he was not illustrated in figure A5). This memory only serves to bolster Umatoy's earlier conjecture

[9] Lotus Development acquired this firm, Iris Associates, in 1994 and IBM acquired Lotus Development thereafter in 1995. Despite these changes, however, Kaufman continues to work with the same group, now under the IBM umbrella.

that engineers left for startups and only managers left for other large firms. Umatoy expressed mixed opinions about information transfer across firms. Consistent with the freshout hiring policy, his firm hesitates to hire from competitors, for fear that they will leave and go back to their original firm. He felt that Applied Materials did not, "give you time for any outside life [that would enable knowledge transfer]." Yet, before starting a project, he reported that Applied Material engineers call their friends (who include colleagues at other firms), contact professors at universities, and read the patent and scientific literature.

In contrast to the seeming lifetime employment of Applied Materials, most of the inventive colleagues of Robert Sprague have left the legendary Xerox PARC. He listed a variety of destinations for his coauthors during the study period, including Spectra Diode Labs (also in figure A4), Komag, Exxon Enterprises, Canadian Research Corporation, and a variety of startups. Most became CEOs, CTOs or the Chief Scientist, 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 startups provided stock opportunities. He divided the movement of technology out of PARC into three categories: disgust, opportunities, and friendly, with the latter being Xerox sponsored and supported. He included Spectra Diode Labs and his own, Michigan based startup, 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 in subsequent years,[10] Charles Kaufman observed two corollary points: DEC was not hiring due to its economic concerns and leaving was considered "kind of 'traitorous.'"[11] In fact,

[10] 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 1st in 1992, only to be displaced a final time in 1993. All three of the bridging inventors we spoke with from DEC departed in 1993.

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

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. [12]

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

We heard one Valley specific story for non-agglomeration, of a scientist that left employment at a large and established firm to work as a self-employed inventor. Even though it was neither a semiconductor nor a computer firm, Raychem had been the Valley’s largest component until being overtaken by IBM in 1987. Michael 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. The environment changed in 1983, however, when non-technical management assumed control. Without technical foresight from the top, politics became rampant, and senior inventors and scientists left in great numbers. Destinations included the medical device industry, fiber

[12] Again 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 startup. They were rehired following the startup’s failure and given a party upon their return.

optics, small startups, 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 medical, chip and board fabrication, and optical industries. Raychem’s management repeatedly failed to seize these opportunities. For example, Advanced Cardio Systems asked for help in applying Raychem’s electron beam techniques (in the medical pacemaker market, which was unrelated to Raychem’s current markets). Raychem management turned the request down, out of fear of losing advantage in their current markets.

Froix left Raychem in 1985 out of frustration - without another job, except for a part-time teaching position at the University of San Francisco. He decided to invent a material that would decrease the clotting that occurred on the surface of artificial hearts (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 (assumedly without corporate approval), and 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 cold-called Prof. Robertson in 1986 and asked for help. Robertson replied that he would leave the decision to his best graduate student. The student agreed to help but didn’t begin working until midnight, however, so Froix would sit on the stairs next to the lab from 6:00 pm, when the building was locked, until the student arrived many hours later. The collaboration worked and Froix perfected his invention. Froix 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 startup, Quanam, which has been bought by Boston Scientific. 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 by stent cell.

As can be seen in figure A3, Froix did not have many collaborators at Raychem, but he has stayed in touch with them and other former colleagues over the years, mainly for job searches. When asked if he has discussed technical matters within this network over the years, he strongly concurred. Froix's experience provides a compelling story of inventive tenacity in the interstices of the Valley's technological ecosystem. It is difficult to understand how representative his experience has been, however, without a better understanding of the sampling distribution of inventors and their likelihood to violate corporate and university rules. The Valley might be more supportive of such inventors, but Boston inventors may also have had after hours access to firm, and university laboratories or professors at MIT or Harvard that are willing to support their research. Determining how widespread such practices are in Boston or any region would require inventors to admit to violation of corporate, and university rules, and possibly put their jobs at risk. Hewlett Packard had an oft-repeated story (told by the protagonist in Packard 1995), however, 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 be locked again. They felt that supporting an inventor's creativity was far more important than any employee theft that might occur. Such stories remain anecdotal, but consistently suggestive that strong engineering cultures (wherever they might be) place creativity before financial and proprietary concerns.

Paul Koning expressed skepticism regarding a generous flow of information or resources across collaborative linkages and he specifically felt that Froix's story was incomplete. In comparing his own relatively 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 of unseen equity relationship underlying this seemingly informal cooperative behavior.

Boston specific reasons for non-agglomeration

We found a wide variety of idiosyncratic reasons for Boston's non-agglomeration. Even with a wide variety of academic opportunities, MIT graduates tended to take academic jobs outside of the Boston area. They also took employment with private firms outside the area as well. Continued agglomeration of the DEC component was also hampered by management's encouragement of internal rivalry and competition. Engineers at Honeywell, another large component in the time period, only collaborated with Intel inventors and other Honeywell inventors outside of the region. The heavily academic focus of the Boston area also resulted in less emphasis upon patenting and more upon the publication of scientific papers.

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 the largest component in Boston shifted from one year to the next until 1993. [13] During the 85-89 window, the largest component in the Boston network consisted primarily of MIT affiliates. Richard Cohen of the Division of Health Sciences and Technology served as a key bridging point among these individuals. Reflecting upon his involvement on a 1985 "cut-patent," or 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 upon 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 these same individuals often proved to be some of the most compelling candidates on the job market several years later (when they were ultimately too senior and well compensated to be drawn back). Cohen's comments imply that elite universities might actually have less influence on local agglomeration, since their graduates are more likely to leave the area in search of comparably elite positions.

---

[13] 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 resumes its rank as 1st 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 agglomeration of inventors across organizations as diverse as MIT, Polaroid, Reebok, Kopin Corp., Motorola, Mobile Oil and United States Surgical Corporation, among many others.

Nonetheless, based on his experiences at MIT and as the founder of Cambridge Heart, Inc., Cohen reported that biotech information flows quite freely - within the academic community - and consequently identified academia as a particularly fertile environment for the execution of “proof of concept” research. 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 knowledge creation or exchange through the subsequent design or development of corresponding commercial products. Compounding this problem, then, Cohen found that the economic interests of those businesses left to bring such products to market further inhibited any flow of information specific to the commercialization process. Given that Boston technology relies to a much greater extent upon university patents and published science (see illustration A20), its social networks might actually be more connected than the Valley’s.

Moreover, within the larger biotech industry, Cohen also felt that the business of medical devices was quite distinct from that of the pharmaceuticals produced by those we interviewed in the Valley. Specifically, he noted that the smaller end market for devices tended to sustain much smaller, less generously funded, and perhaps also 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 resources of a large firm. The three key reasons for the subsequent fragmentation of Cohen’s network component appear to be the departure of his student collaborators from the Boston region, the practical disconnect between “proof of concept” and commercialization research efforts in biotech, and the small and perhaps even insular nature of medical device companies.

Kaufman, Koning, and Perlman also emphasized how culture influences differential patenting prolificacy across organizations, and noted the role of DEC’s explicit patenting policies in motivating them to identify their patentable work proactively. These inventors felt these policies implicitly encouraged employees to identify other collaborators for each of their patents, among other reasons, because DEC awarded the full patent bonus amount of $500 to as many as three inventors per patent. As such, those with ideas to patent were often inclined to seek out collaborators (whether needed or not) in order to "share the wealth", and encourage others to "return the favor." Additionally, DEC granted a steeper set of awards for cumulative patenting (at $5000 for 5, $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 further noted that DEC displayed a cyclic pattern based on patenting objectives that were established in response to a cross-licensing relationship with IBM. Specifically, IBM had a cross-licensing policy by which it would grant a company the use of all IBM patented technologies in exchange for IBM's right to use that company's patented technologies. However, the size of IBM's fee for this arrangement was inversely proportional to the size of the company's portfolio of patents and, therefore, DEC business managers recognized a value to patents that fell well beyond more traditional purposes like licensing revenue or protection from imitation.

These policies should have made the DEC component more robust in our analyses, however, and the persistent fragility in the firm's networks is consistent with its reputation for fostering competition between work groups. Paul Koning confirmed this reputation, and described how Ken Olsen, DEC's founder and CEO, routinely created competing internal groups as a means to fuel rapid progress. Koning went on to note that the practice severely strained internal morale and inter-departmental cooperation.

Patenting policies also influenced the 2nd largest connected component in Boston during both the 85-89 and 86-90 windows, composed largely of scientists and engineers at General Telephone and Electric (GTE). Two among these inventors were Jakob Maya and Alfred Bellows. When asked why the GTE component did not agglomerate to rise in size rank from 1989 to 1990 and, more significantly, why it did not persist as the largest connected component after displacing that of DEC in 1991, Maya provided two primary explanations. First, he explained that people at GTE (and his field more broadly) typically view patents as a very costly expense (i.e. 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.[14] Maya estimated, based on his own patent collaborator network graph from 1985-1989, 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 papers with other authors (and at times not in the same firm) as he did patents.[15] Second, the relative weakness of the GTE component in Boston was probably much further attenuated when GTE Sylvania sold its lighting business to Siemens' Osram in 1992. 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.[16]

Honeywell, the 6th largest connected component in the Boston network during the 86-90 time window, also suffered from a series of contractions. Ultimately a lifetime employee at Honeywell, Thomas Joyce began his career there in 1960, and remained through multiple mergers, repeated corporate renaming, and several departmental job moves until retiring recently in 2000. Joyce provided three reasons for why the Honeywell component did not agglomerate to rise in size rank from 1989 to 1990 (rather, it dropped by one from 5th to 6th). First, collaboration at Honeywell was oriented more globally than locally, such that he recalls working with a number of Honeywell-employed Europeans at the time, but never exchanging information with anyone outside of 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

[14] Our patent data supports this assertion. Patents also cite non-patent references and these are mostly scientific, peer-reviewed papers (Sorenson and Fleming 2002). Boston inventors cited 30% more science papers on average than Valley patents since 1975. Boston also had a greater proportion of academic patents over the entire time period as well.

[15] Therefore, Maya's comments further support the notion that the norms of openness and patenting are industry specific, as introduced earlier in our discussion of the biotech managers we interviewed in Silicon Valley.

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

proprietary nature of the chip design work being done there. Second, he noted that the entire group with which he was linked consisted of a relatively more mature cohort of inventors or “older hangovers from the 60s and 70s,” many of which had more pressing family concerns or were nearing a reasonable age for retirement and had long-term Honeywell pensions to consider (in choosing not to leave, and thereby serving as bridges to link the Honeywell component to other Route 128 components). If Boston firms made their pensions contingent upon retirement with the firm, internal labor markets for Boston firms would be stronger, and this would certainly have hampered the older firms from becoming linked into other components. Third, Joyce added that Honeywell’s chip designers found themselves “under the secrecy cloak of Intel by the early 90s” to the extent that collaborating with Intel required Honeywell to willingly forego the option to share knowledge elsewhere (publicly or otherwise). Our patent data strongly supports Joyce’s description of Honeywell’s insularity. Of the 81 inventors in the 86-90 window, 11 had collaborated on one or two of three non-Honeywell patents, while Honeywell held the 91 remaining patents linking this component.

Taken collectively, these inventors’ comments broadly suggested that the corporate policies and strategies of the dominant firms in the Boston region at the time often served to blunt agglomeration both *within* and *across* firms. For example, the DEC component appears particularly weak despite DEC's strong incentive program for patenting, for instance, at least in part because its founder fostered unproductive internal competition. Likewise, the GTE component appears to have been similarly fragile, at least initially, as a result of an entirely distinct attitude toward patenting. However, invention also stagnated at these firms as a consequence of even more sweeping strategic business decisions – to pursue proprietary technologies (at DEC, Data General, and Honeywell) and selling ownership to an acquiring firm (at GTE and Honeywell). In the former case, invention suffered as firms struggled with the negative economic outcome of their decision and inventors were constrained in their careers by proprietary skill sets. In the latter, many inventors reportedly left their respective fields, retired, or focused their efforts more upon the political maneuvering required to hold onto their jobs in turbulent times than on their inventive pursuits.

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 decisions to remain in the same firms were 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 actually weave back in to these firms' proprietary technological strategies - and thereby establish 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 lent significantly to the ultimate failure or disruptive acquisition of at least three dominant firms in the area, including DEC, Data General, and Honeywell.

Ruling out Alternative Explanations

To supplement these detailed analyses of the individual components, we also investigated a number of plausible alternatives. Based on additional analyses of the patent data, Boston inventors were slightly more likely to work alone (see illustration A13), be self-employed and therefore own their own patent (A14), and work with a fewer number of collaborators (A15). The tie density was similar across the regions over time (A16). The regions also demonstrate similar age and diversity of technology and number of assignees per inventor (which indicates that total personnel movement was actually quite similar in the regions, see A17, A18, A19). The differences are slight, however and none of them demonstrates an abrupt transition around the time of study that might have caused the agglomeration processes we observed.

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. For example, 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 A6 illustrates one example of this process, the disintegration of the MIT/Foxboro/Dana-Farber component, Boston's largest component in 1985-1989. Its lighter color ties mark the patents that expired by the following year (basically, patents that had been applied for in 1985). This illustrates how the component lost important bridging nodes 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 than in the Valley (and indeed, is by far the most robust of any component we analyzed).

We tested the hypothesis at two levels of analysis, first at the inventor and then the patent. Figures 4 and 5 illustrate the inventor level of analysis for the first and second largest components in the regions (illustrations for the 3rd through 6th component comparisons looked qualitatively similar to the 1st 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 5 as an example. The point 0.05 on the x axis indicates that 5% of the nodes have been removed from the originally 2nd largest components of Boston and the Valley. At this point, the y-axis indicates that the minimum proportion of nodes that remain connected is about 30% for the Valley and over 40% for Boston. The graphed points are summary statistics (minimum, median, and maximum), of 50 samples for each data point. We sampled because of the combinatoric explosion of exhaustively calculating all possible choice combinations.

Figure 4 reveals very similar robustness for the two regions. Figure 5, however, illustrates that the Valley component is more vulnerable to the loss of a few nodes. The steep initial drop in figure 5 for Silicon Valley indicates that the loss of a few key inventors quickly breaks the component up into much smaller pieces – similar to the graphical process illustrated in figure A6.

To confirm our results, we repeated the analysis at the patent level. We calculated the extent to which a component is disconnected as the proportion of inventor dyads that would not longer be able to reach one another after a patent is removed. Our calculations generate a higher value when the removal of a patent results in the creation of many new components and the inventors are divided equally among components. We then measure the overall vulnerability of each network by taking the mean of the proportion of inventor dyads disconnected by each of the patents in a component.

Table 2 illustrates robustness results. What is most striking is that there does not seem to be any systematic difference between the vulnerability of components in the two regions. The mean vulnerability over all the Boston components is 0.0241 and 0.0272 over all Silicon Valley components. Consistent with the inventor analysis, the second component appears to be much more robust in Boston. Furthermore, since the components are now quantifiably comparable, it becomes obvious that it is more robust than all other analyzed components. Inspection of figure A10 does indeed reveal a dense component with redundant connections and multiple cycles. Both of these analyses suggest that the Valley's agglomeration was not caused by its components being able to hold together better in order to merge with other components.

Since component robustness did not seem to explain the Valley's agglomeration, we ran an experiment to quantify the impact of IBM's post-doctoral program. Based on our interviews with Campbell Scott, we split his patent authorship into two separate people, by assignee ownership (Scott's patents with IBM became one person and those with BioCircuits became another). We performed similar splits on Todd Guion and Victor Pan. These splits resulted in a 30% decrease in the size of the Valley largest component in 1990, 11% in 1992, and 9% in 1994. As might be expected with five-year windows, we observed no effect in subsequent years. This sizable effect is still a lower bound to the overall and cumulative impact of the program, since we did not consider the dozens of other post-docs that moved through IBM en route to other jobs in the Valley. [17]

[17] We have asked IBM to help us identify all of the post-doc program patentees since 1975 and are awaiting an answer.

Discussion

The secondary motivation for this research was to understand whether and how information flows across such indirect linkages. We are struck by the bi-modal distribution of attitudes on the issue. Most of the inventors from both regions expressed similarly laissez-faire, open, and positive attitudes towards information flow. Many of their stories described an effort to evade management efforts 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, namely Salvador Umatoy, and particularly Hans Ribi and Pyare Khanna. Pyare Khanna explicitly described spillovers as bad, that it took one year to train a scientist, and 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, in order to avoid their being poached by rival Valley firms. Prior to moving to Pleasanton, and then Fremont (a city nominally within the confines of Silicon Valley), his firm had been in Concord, California (about 50 miles north of and well outside the Valley). He preferred this location because salaries were 20-30% lower, personnel tended to be more stable, and people were less likely to leave. He remained noncommittal about why he moved his firm to Silicon Valley, and only commented that, "Here there is the nucleus of growth." He opined that Kendall Square, in contrast, had no industry, only universities. [18]

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

[18] An observation that may be out of date, given the recent flurry of Biotech activity in the Square.

terms” in order to acquire a first mover/first to market advantage (as is far more common among products which 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, he believed that the majority of *both* motivations operate under 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 vs. 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 location in fast paced technological regions like Boston and Silicon Valley, there clearly exist many counterbalancing attractions. Firms can access qualified personnel, and while they must pay them more and still risk losing them more easily, at least they can find their needed talent. Access to university research and the latest industrial buzz also enhances the value of location in the Valley or Boston.

Conclusion

Why do regional inventor networks agglomerate or disintegrate? We found many influences that hamper agglomeration, including the breakup of firms and the related uncertainty that sap morale and inventor productivity, the dispersal of graduates to jobs outside the region, the departure of senior inventors to startups and self-employment instead of other established firms, firm policies that discourage collaboration, and proprietary strategies that make such collaboration unproductive. We found fewer influences that enhance agglomeration, including collaboration across academic and firm boundaries, collaboration within large firms, hiring of local university graduates, and finally, post-doc fellowships that seed local businesses with technically trained personnel.

While there may have been more stories of information flow and informal collaboration in the Valley, they did not differ qualitatively from those in Boston. Indeed, if Boston's scientific and academic networks were analyzed, they would probably reflect greater openness than the Valley. With regards to patent networks, Silicon Valley is indeed more connected in the sense that inventors are apparently more willing to create far-flung contacts (similar to a "small world" network, see Watts and Strogatz 1998 and Fleming, Juda, and King 2003). Such exploration, however, leaves their local networks less cohesive and less robust. The differences remain subtle – like human genetic material and races, there probably exists far more variance between industries and organizations than regions.

The only truly idiosyncratic stories in the Valley were the itinerant creativity of Michael Froix and the IBM post doc program. While it was hard to assess how representative Froix's experience was, we were able to demonstrate quantitatively how the post-doc program contributed to a substantial portion of the Valley's agglomeration advantage. IBM has since cut the post-doc program back, given the firm's financial problems in the early 1990s. Other firms, however, such as Hewlett Packard, have begun similar programs. IBM modeled their program on Bell Lab's post-doc program (which given the breakup of AT&T, no longer exists). William Risk and John Campbell Scott provided a variety of reasons and motivations for the program. First, the post-docs provided cheap labor to the firm. Second, there was the perception of value in new people with fresh ideas, and third, IBM assumed that such people would come in and then go away as ambassadors for the firm. They did not mention the concerns about proprietary information loss 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 at the time, "…the research division was set up by scientists with foresight," according to Scott. Their foresight had an impact well beyond the walls of IBM. Their success reminds us how individuals can build institutions that in turn shape technological and economic history.

The research implies a number of policy considerations. While regional planners should encourage employee movement in order to enhance spillovers, they must also convince firms that it is worth their while to tolerate such movement and proprietary loss. Planners can encourage movement in a variety of ways, such as mobile pensions and retirement support, weakened or un-enforced non-compete and non-disclosure agreements, post-doc and visiting scientist programs, contingent and temporary technical employment (Gura 2004), and venture capital that supports new firm formation. At the same time, however, planners must convince firms that it is worth competing in the fast lane. For example, a firm looking for technological spillovers from other industries would do well to locate in a region with the appropriate industries but without direct competitors (of course, the advantage will be fleeting if the region also encourages start-ups). A firm might also invest in better downstream capabilities such as product development and marketing. Since these are still very difficult – but better understood - capabilities to master, firms would do well to embed themselves within a fertile region, knowing full well that their only hope is to commercialize the fruits faster than their competitors.

References

Almeida, P. and Kogut, B., (1999) "Localization of Knowledge and the Mobility of Engineers in Regional Networks." Management Science 45: 905-916.

Albert, M. B. and F. Narin, D. Avery, P. McAllister (1991), "Direct Validation of Citation Counts as Indicators of Industrially Important Patents," *Research Policy*; 20:251-259.

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

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

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

Beam, A. (1989) "Our Technology Graveyard," *The Boston Globe*, July 26 1989, Economy p21.

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

Clark, D. (1991) "Newcomers Put Stamp On Silicon Valley, " *The San Francisco Chronicle*, July 8 1991, Business pB1.

Cohen, F. (2003), personal interview, Natick, Massachusetts, February 13.

Cohen, W. and D. Levinthal (1990), 'Absorptive Capacity: A New Perspective on Learning and Innovation,' *Administrative Science Quarterly*, 35,128-152.

Fleming, L., (2001). Recombinant Uncertainty in Technological Search, Management Science: Volume 47:1, 2001: 117-132.

Fleming, L., and C. King, A. Juda. "Small Worlds and Regional Advantage," working paper, Harvard Business School, 2003.

Florida, R., and Kenney, M. (1990) *The Breakthrough Illusion*, BasicBooks: New York, NY.

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. and H. Kallal, J. Scheinkman, A. Shleifer (1992), "Growth in Cities," *The Journal of Political Economy*, Chicago, Vol. 100:6: 1126-1153.

Graham, R. (1989) "'Miracle' Proves a Mirage; New arrivals find too little of high-tech boom, too late," *The Boston Globe*, July 28 1989, Metro/Region p13.

Grove, A. (1990) "The Future of the Computer Industry," *California Management Review*, 33(1):148-161.

Granovetter, M., 1973. The strength of weak ties. *American Journal of Sociology* 78, 1360-1380.

Gura, T. (2004), "Joining a Trend, Scientists Increasingly Say 'Call My Agent'", *Science* Vol. 303, pgs. 303-305.

Henderson, V. (1997), "Externalities and Industrial Development," *Journal of Urban Economics*, Vol. 42:449-470.

Henderson, V. and A. Kuncoro, M. Turner (1995), "Industrial Development in Cities," *The Journal of Political Economy*, Vol. 103:5:1067-1090.

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

Kenney, M., and von Burg, U. (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):483-499.

Leslie, S., and Kargon, R. (1996) "Selling Silicon Valley: Frederick Terman's Model for Regional Advantage," *Business History Review*, 70:435-472.

Marshall, A. (1920), *Principles of Economics* (8th Ed.). London: Macmillan.

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

Newman, M. (2000). "The structure of scientific collaboration networks." *Proceedings of the National Academy of Sciences of the United States of America* 98, 404-409.

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*, eds. Nohria, N. and R. Eccles, Boston, Harvard Business School Press.

Packard, D. (1995), *The HP Way: How Bill Hewlett and I Built Our Company*, HarperCollins Publishers, New York.

Robertson, P., and Langlois, R. (1995) *Firms, Markets, and Economic Change: A Dynamic Theory of Business Institutions*, Routledge: New York, NY

Rosegrant, S., and Lampe, D. (1992) *Route 128: Lessons from Boston's High-Tech Community*, BasicBooks: New York, NY.

San Jose Mercury News (1989), "Stalled Out on Route 128; Boston's Tech Machine Breaks Down," August 3 1989, p1E.

Saxenian, A. (1990) "Regional Networks and the Resurgence of Silicon Valley," *California Management Review*, 33(1):89-113.

Saxenian, A. (1994) *Regional Advantage: Culture and Competition in Silicon Valley, and Route 128*, Harvard University Press: Cambridge, MA.

Saxenian, A. (1999) "Comment on Kenney and von Burg, 'Technology, Entrepreneurship, and Path Dependence: Industrial Clustering in Silicon Valley, and Route 128,'" *Industrial, and Corporate Change*, 8:105-110.

Schweikart, L. (2000) *The Entrepreneurial Adventure: A History of Business in the United States*, Harcourt College Publishers: Ft. Worth, TX.

Simon, J. (1989) "Job Chill on 128; with cutbacks and slowed growth the hiring sizzle is gone," *The Boston Globe*, April 30 1989, Economy pA1.

Singh, J. (2003), "Inventor Networks and Inter-Firm Knowledge Diffusion," Working paper, Harvard Business School.

Sorenson, O. and L. Fleming (2002), "Science and the Diffusion of Knowledge," Harvard Business School Working Paper 02-095.

Stein, C. (1989a) "128; Why it will never be the same," *The Boston Globe*, January 3 1989, Economy p21.

Stein, C. (1989b) "Along Route 128, high tech hits lows," *The Boston Globe*, August 1 1989, Metro/Region p1.

Watts, D., Strogatz, S., (1998). Collective dynamics of small-world networks. *Nature* 393, 440-442.

ZIPList5 MSA (2003). Downloaded April 24, 2003, from CD Light, LLC: www.zipinfo.com/products/z5msa/z5msa.htm.

Appendix A: Matching Algorithm

We extracted source data on all granted U.S. patents from 1975 to 2002 inclusive (U.S. Patent Office 2003), 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' home towns, detailed information about its technology in subclass references (over 100,000 subclasses exist), 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 other inventors with whom the focal inventor has co-authored at least one patent. The database includes 2,058,823 inventors, and 2,862,967 patents.

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 comparisons are positive, the algorithm then requires an additional non-name similarity: hometown city, and state, corporation (via assignee codes) or technology (via technology sub-classifications). We also implemented a common name parameter that ignored the additional match requirement if the last name comprised less than .05% of the U.S. population, as determined by the U.S. Census Bureau (get website).

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

The analyses presented relied upon all patents with at least one inventor within the region. Thus, if inventors from inside and outside a region co-authored the same patent, the patent (and both inventors) would appear in each region. To explore the sensitivity of this definition, we re-graphed all data with the more exclusive definition. 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 remain unchanged. Figure A20 illustrates the proportion of inventors in the largest component for the exclusive definition. The proportion graph illustrates a less dramatic takeoff for Silicon Valley and Boston, but the divergence point remains at 1990.

Appendix B: Interviewed Inventors

In Silicon Valley:

Michael Froix (counterfactual to William Risk) earned his PhD. from Howard University in physical chemistry. He has worked at Xerox, Celanese, Raychem, Cooper Vision, Quanam, and has also been very successful as an independent inventor.

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

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

Hans Ribi received his PhD in 1988 at Stanford University in biochemistry, and was the CEO of Biocircuits at the time that Glenda Choate worked with John Campbell Scott.

William Risk graduated with an electrical engineering PhD. from Stanford, although he had done his research in applied physics, optics, and photonics. While he surfaced as an important inventor in our study because of his association with Gordon Kino, he also worked with John Shaw.

John Campbell Scott still works at IBM Almaden Research Laboratory in the southern Santa Clara Valley. He earned his PhD. in solid state physics at the University of Pennsylvania, and has worked in materials science for most of his career.

Salvador Umatoy (counterfactual to Glenda Choate) worked in the medical instrumentation industry before coming to Applied Materials in the early 1980s. He remains at the firm, and currently manages mechanical engineers in their design of wafer fabrication equipment.

Robert Sprague (counterfactual to Pyare Khanna) earned his PhD. from the University of Rochester, in physics. He has worked at Xerox PARC since the time period of study, and is also CEO of the Gyricon, a Xerox PARC spinout.

In Boston:

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 Digital Equipment Corporation.

Radia Perlman earned her PhD from MIT while employed by Digital Equipment Corporation. She is currently a Distinguished Engineer at Sun Microsystems and serves on the Internet Architecture Board of the IETF.

Paul Koning worked with Charles Kaufman, and Radia Perlman at DEC before moving to smaller startup ventures. He is currently the founder, and CTO of a successful VC-backed startup situated just outside the Boston area.

Thomas Joyce (counterfactual to Radia Perlman) worked as a logic designer, and patented repeatedly at Honeywell, Honeywell Bull, and Bull until his recent retirement.

Jakob Maya (counterfactual to Paul Koning) holds a Ph.D. and is currently leading research in state of the art lighting technology at Matsushita Electric Works R&D Lab. Before joining Matsushita, Maya was employed similarly as a Director of R&D at GTE.

Alfred Bellows (counterfactual 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.

Richard Cohen (counterfactual to Perlman) holds an MD and PhD. 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.

Appendix C: Patent robustness analysis

One obvious explanation for the greater agglomeration in the Silicon Valley network is that its components are more robust. We define a component as robust if contains enough redundancy to ensure that the removal of a few nodes does not cause it to become disconnected. When a component is robust the creation of a new tie from another component to any node within the original component is more likely to cause agglomeration since it is assured that the newly connected target node will not become disconnected from the original component.

To test the robustness of the network we chose to work with the two-mode network data (Wasserman and Faust 1994). These data contain nodes representing both patents and inventors. The relation graphed is the authoring relationship, therefore inventors are tied to patents they have authored and tied to each other only indirectly though patents. Using these data we examine the consequences for the connectivity of each component when individual patents are removed.

We focus on patents rather than inventors here because the inclusion of patents is more contingent than the inclusion of inventors. Patents may fail to be included for two reasons. First, the relevant innovation might fail to be invented. If researchers' undertakings are unsuccessful then no patent would ever be filed. Since the invention process is highly contingent one could easily imagine that any of the inventions currently included in the data might not have been successfully developed or conversely that unfruitful research conducted differently might have resulted in patents that never were. Although one could also easily imagine that particular inventors might fail to develop ideas successfully, their inclusion in the network is less contingent. Because most inventors are acting as employees of an organization, we can assume that even if a particular individual had chosen a different career path (and thus 'never existed' as far as the network is concerned), the organization would still employ someone within that inventor's role and that the alternative employee would have a similar pattern of inventions.

Second, patents may also fail to be included in the data because they do not fall within the five year window used to construct the data sets. If the connectivity of the components is highly dependent on the inclusion of individual patents then the connectivity of the networks could be as much a consequence of the window selected as of the structure of the networks.

We limit our analyses to the six largest components from 1989, the key year immediately preceding the surge in connectivity in the Silicon Valley. For each of these 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 a component (c)existing after a patent is removed and N is the number of inventors in the original component; c is a component created by the removal of a patent, 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 inventors in each component, this results in .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 results in breaking the component into 10 components with 9 of these being isolates and 91 inventors in the remaining component .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 co-authors on one patent and no other co-authorships 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 paper. 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 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 and 0.0272 over all Silicon Valley components. Consistent with the inventor 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 agglomeration did not occur because its components were more robust and able to merge with other components.

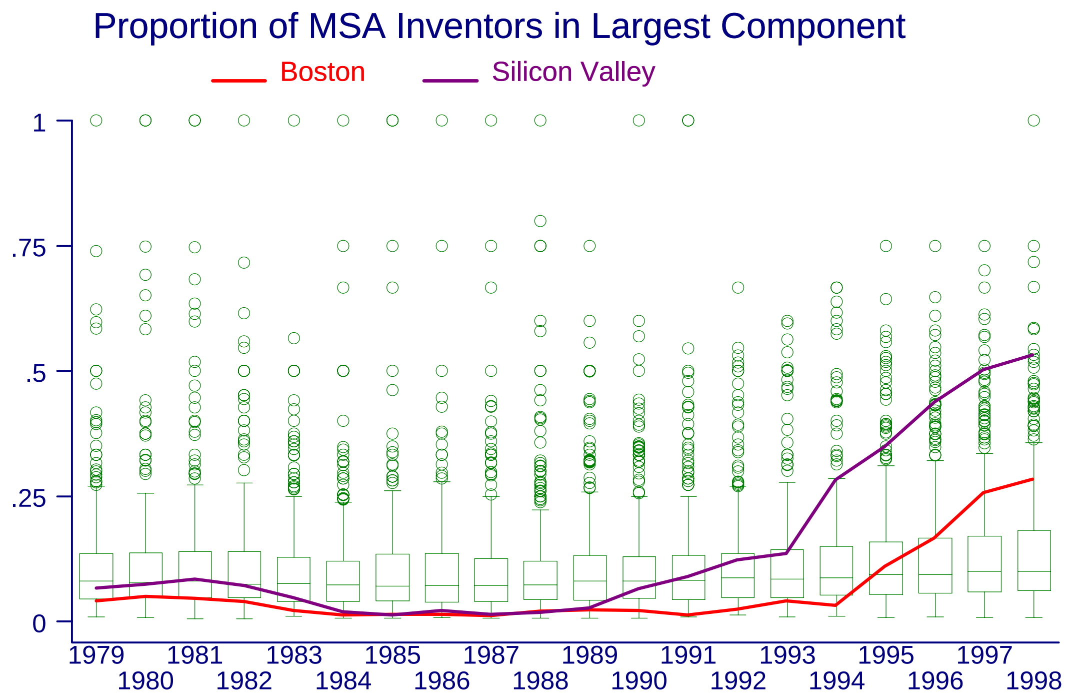

Figure 1: Box plots of relative size of largest connected component to entire network of patented inventor collaborations by U.S. Metropolitan Statistical Area (x axis indicates last year in five-year moving window).

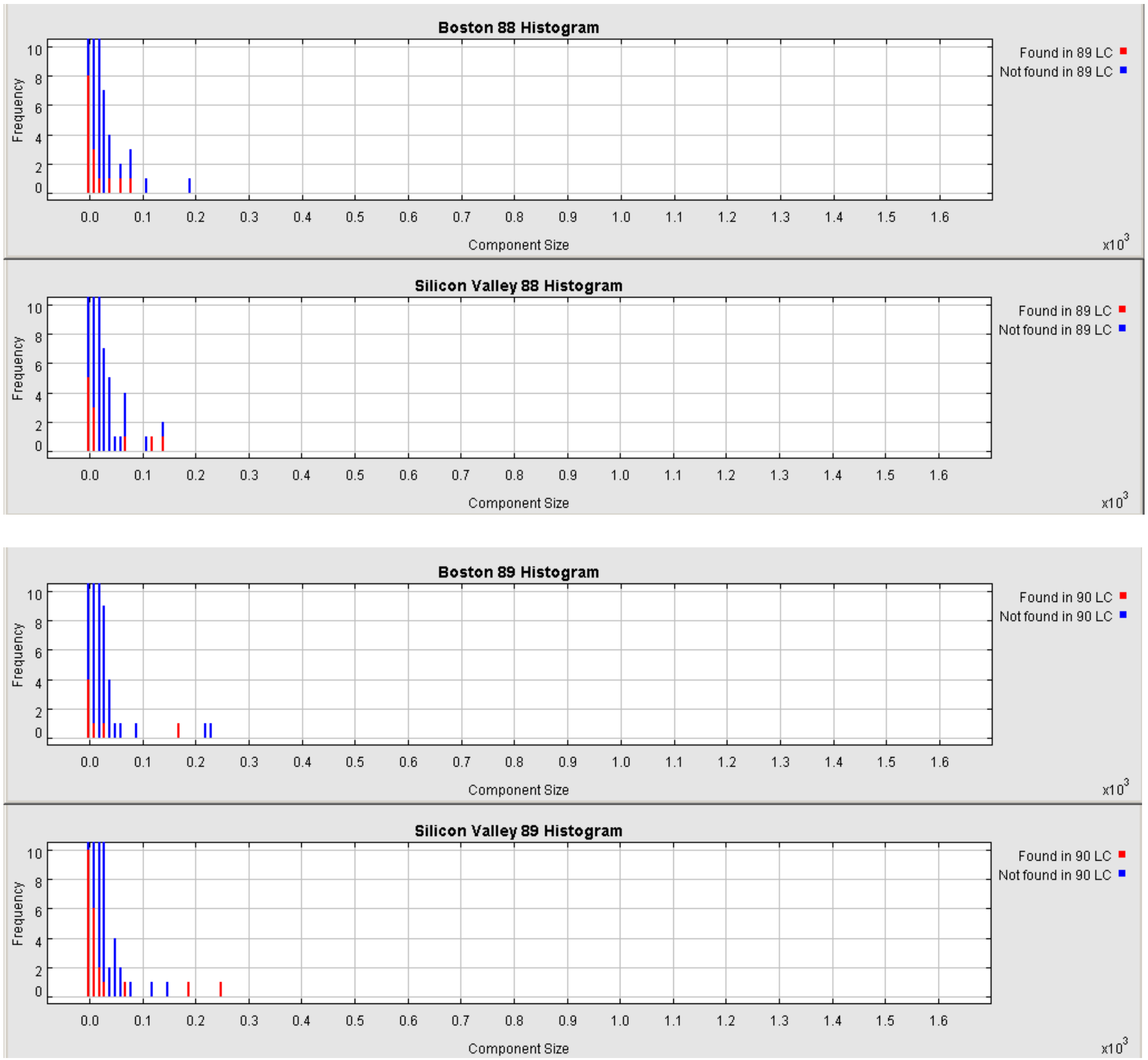

Figure 2: Time series of histograms of component size frequency of Boston, and Silicon Valley. The x-axis identifies the range of possible sizes for network components (demarcated into bins of 10 for readability), while the y-axis reflects, in blue, the number of connected components of a given (bin) 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.

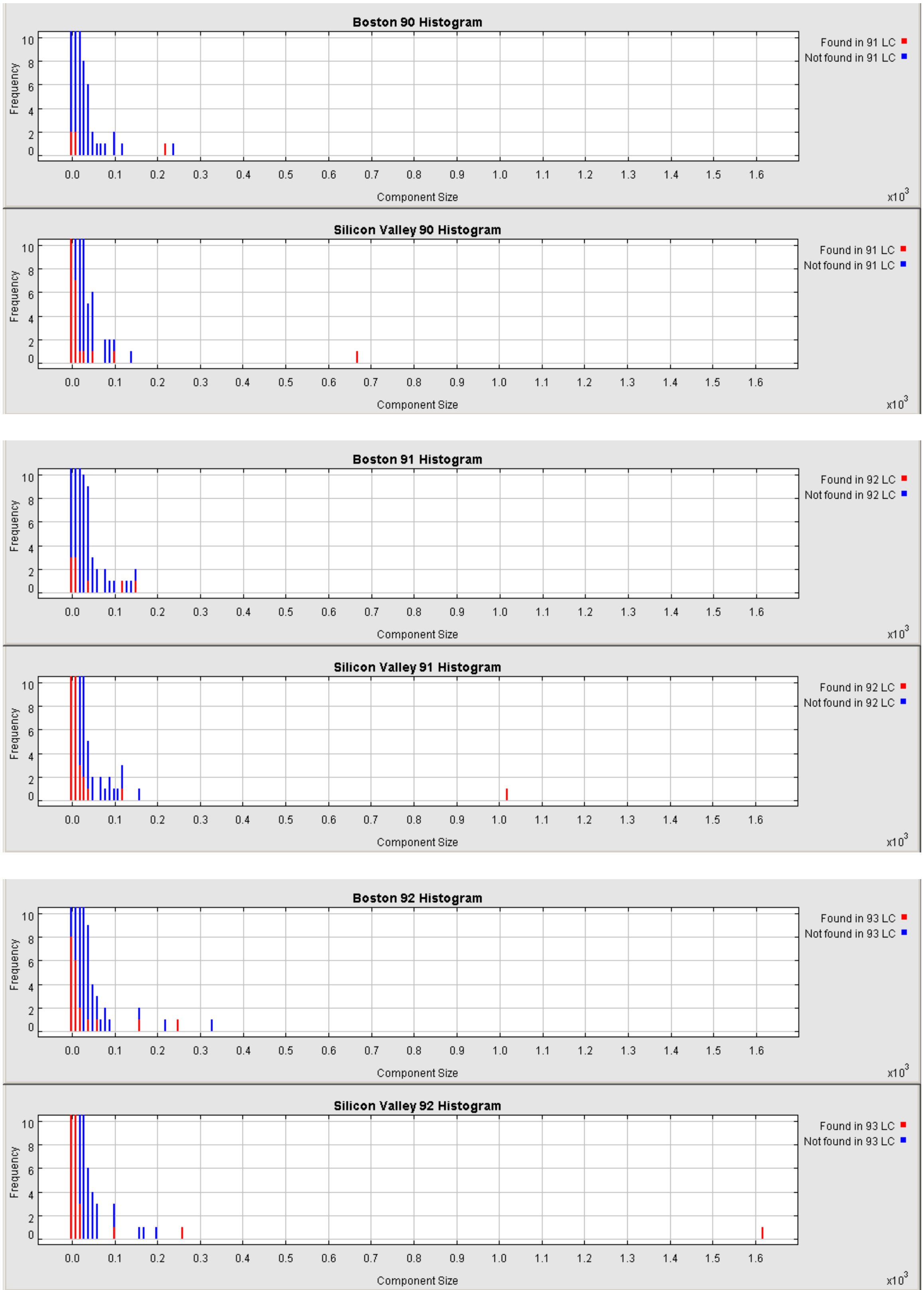

Figure 2 (continued): Time series of histograms of component size frequency for Boston, and Silicon Valley.

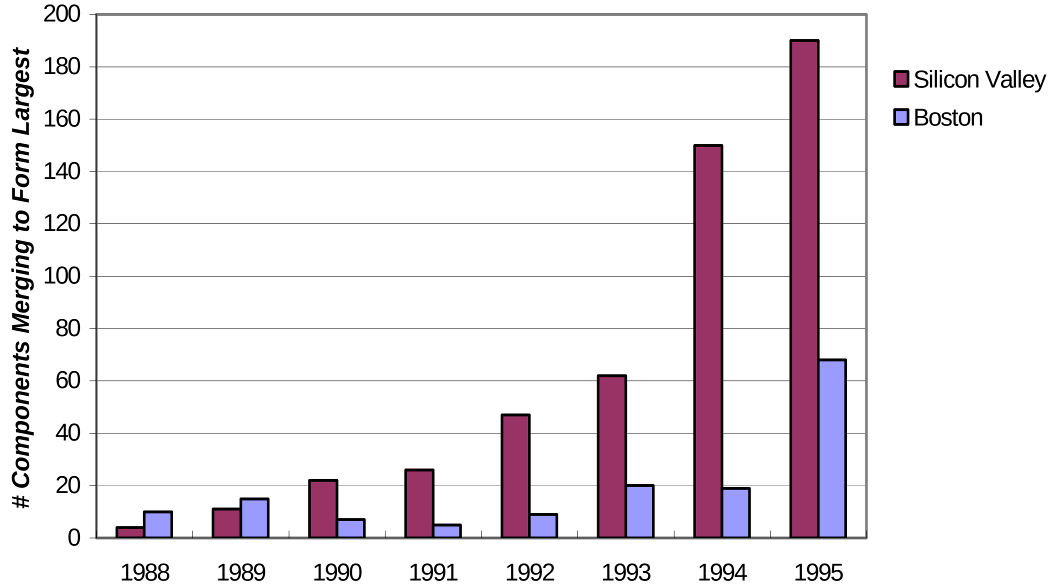

Figure 3: Illustration of how many components from previous year merged into each year's largest component. For example, in 1989, approximately 13 components from the Valley merged into the 1990 largest component, and approximately 16 components from Boston merged into the 1990 largest component. The figure illustrates the runaway agglomeration process that began in Silicon Valley in 1990.

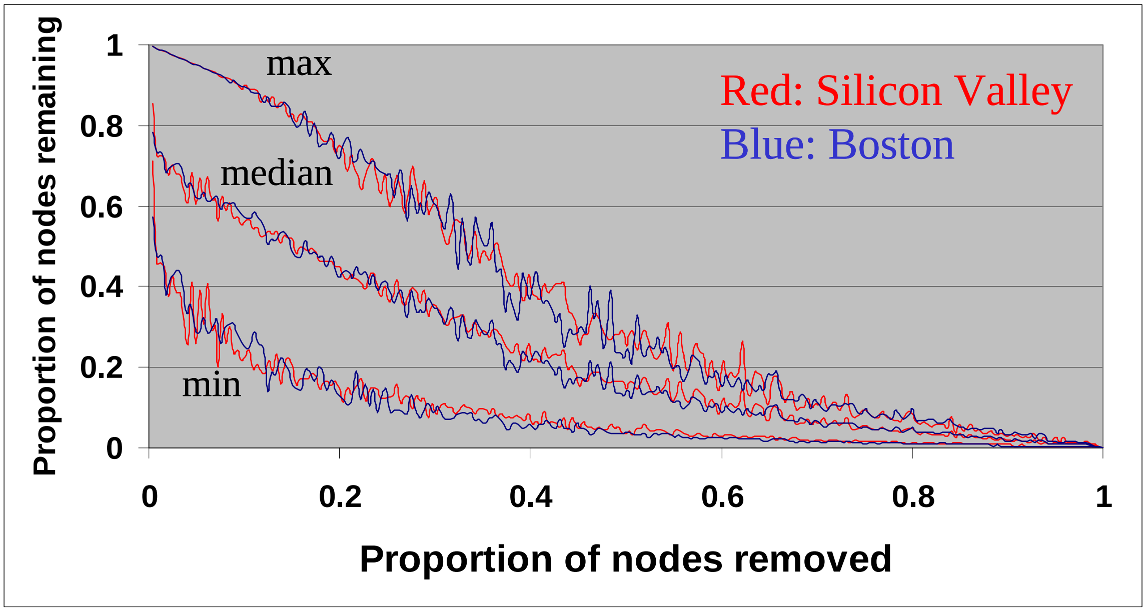

Figure 4: Size of component after removal of specified proportion of component's nodes, for Boston and Silicon Valley's 1st largest components. The y axis illustrates the proportion of nodes that remains connected in the largest resulting component, after a proportion of the original nodes have been removed. The x axis represents the proportion of original nodes that is removed.

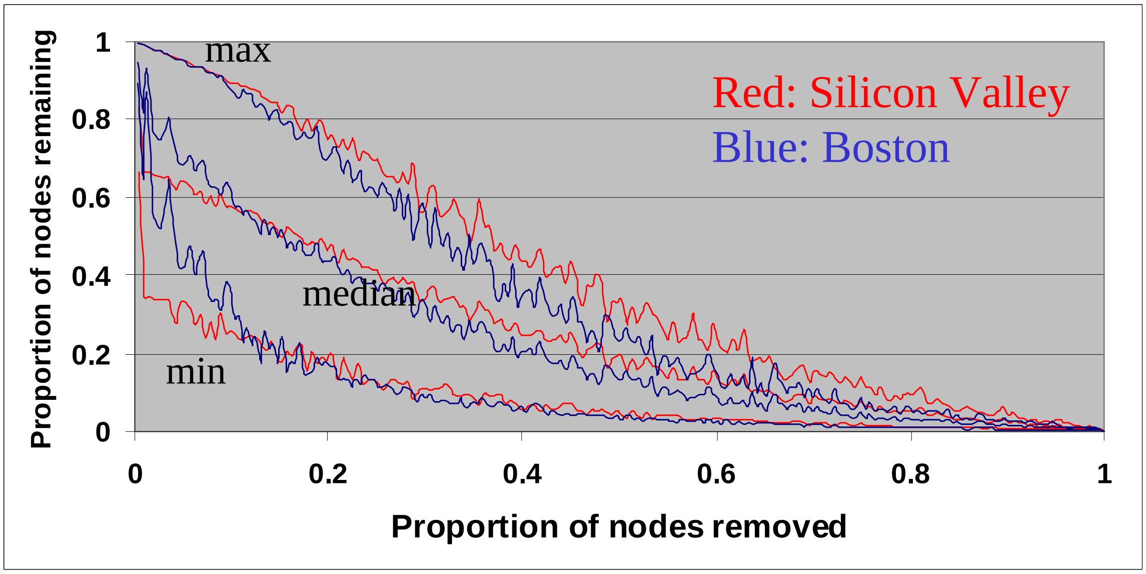

Figure 5: Size of component after removal of specified proportion of component's nodes, for Boston and Silicon Valley's 2nd largest components. The y axis illustrates the proportion of nodes that remains connected in the largest resulting component, after a proportion of the original nodes have been removed. The x axis represents the proportion of original nodes that is removed.

	Agglomeration	Non-agglomeration
Silicon Valley	Local graduate employment IBM post doc 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

Table 1: Summary of reasons for agglomeration and non-agglomeration in Silicon Valley and Boston.

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**

Table 2: Patent analysis of component robustness. 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 deviation is in parentheses.