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

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Abstract: While networks are widely thought to enhance regional innovative capability, there exist fewer longitudinal studies of their formation, change, and influence on information flow and subsequent innovation. Based on an analysis of all patented inventors in the U.S. from 1975 to 2002, we observe dramatic agglomeration of regional inventor networks, first in Silicon Valley, and much later in Boston. We develop a comparative structural history of the regions from 1985 to 1990 and find that Boston remained fragmented, despite a very similar number of patents, inventors, technologies, firms, and overall density of ties, remained fragmented. Based upon interviews with inventors who did and did not create ties across each region's network components, we illustrate the importance of "academic" institutions, both educational and proprietary, for linkage and information flow. Such institutions enabled the earlier agglomeration of Silicon Valley, by encouraging the movement of young inventors into innovative brokerage positions between heterogeneous inventor networks.

Introduction

It has become increasingly fashionable to identify social networks as a crucial contributor to regional innovative capacity (Marshall 1920; Piore and Sabel 1984; Krugman 1991; Stern and Porter 2001). Network advantages have been argued to arise from a wide variety of phenomena, including improved customer/supplier relations, more efficient venture capital and legal infrastructure, and increased knowledge spillovers between firms and regional institutions. Knowledge spillovers are thought to be particularly crucial in regions that encompass fast developing technologies, such as semiconductors and more recently, biotechnology. Spillovers correlate with increased labor mobility (Angel 1989) and relaxed enforcement or legal proscription of non-compete covenants (Gilson 1999). Saxenian (1994) makes the functional argument between networks and innovative capacity in her historical case comparison of Boston and Silicon Valley. She proposes that the Valley's rapid labor mobility, collective learning, inter-firm relationships, informal knowledge exchange gave it a decisive edge in competing against the more secretive and autarkic firms of Boston.

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

The opposing arguments for causality immediately raise the suspicion of co-evolution. Surely networks influence regional advantage and are in turn shaped by regional success or failure? While rich in historical detail and nuance, much of the current discussion about networks and regional advantage remains static (for important exceptions, see Owen-Smith and Powell xxx). The implicit assumption beneath the current discussion is that networks differ across regions but remain essentially unchanged within them. If this assumption were untrue – and could be cleanly unpacked – the discussion could be greatly enriched.

With these goals in mind, we describe how regional collaboration networks form amongst inventors and how those collaborations influence information flow and subsequent innovation. We compare the structural histories of the patented inventor co-authorship networks of Boston and Silicon Valley during 1985-1993. Following Fleming, King, and Juda (2004, see figure 1) we first 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. We investigated this divergence by focusing on the actual ties that inventors created – or failed to create – across the dominant network components within these two regions.

While inventors move jobs and create collaborative ties for a wide variety of reasons (Gulati and Gargiulo 1999), our data highlights the importance of "academic" institutions in the creation of ties across regional organizations. Much of the difference in agglomeration [1] can be traced to Stanford doctoral students taking local employment, while MIT students left the region. We also find that a single institutional program, namely the post-doc fellowship program at IBM's Almaden Valley Labs, was responsible for 30% of the Valley's initial agglomeration. Young inventors play a particularly important role in the process or regional agglomeration; while older inventors move to startups (and are less likely to move in general, see Angel 1989), young inventors move from graduate school through private firm post doc programs and other positions within large network components. Institutions, both public and private, serve as the

[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.

agglomerative glue that knits inventors and regions together. Such glue ultimately enables young inventors to bridge technological communities and broker new technological combinations.

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

Data and Methods

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 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 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 illustrate 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. Even though the process begins with the linkage of larger components, it reaches a critical mass whereby the largest component begins to suck in components of all sizes.

[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.

Qualitative Methods

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 mean degree of collaborations, 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), 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). Finally, we interviewed Robert Stewart, based on his compelling position at the center of the disintegration of Boston's largest component.

We were able to contact many of the linking and counterfactual inventors we identified. We interviewed them mainly 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 2004) and that agglomeration processes improve regional inventive productivity (Fleming, King, and Juda(2004), we also asked them about information flow across the illustrated linkages (the second motivation for the paper). Finally, we simply asked them what they thought might cause the agglomeration processes we observed.

To supplement these detailed analyses of the individual components, we also investigated 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. Finally, even though universities were patenting more over the time period, the elite schools such as Stanford and MIT did not change their patenting rates greatly (Mowery et al. 2001). Furthermore, given that Boston had more university patents than the Valley, this should have increased agglomeration in the region.

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, patenting policies, and product life-cycles.

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. [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).

[4] Each node corresponds to an inventor and network ties correspond to co-authorship of at least one patent. A1 colors the nodes by firm and A2 colors them by technology. Node size in A1 corresponds to future prior art citations to the inventor's patents over the five year time period and can be interpreted as the importance of the patent holder's inventions (Albert et al. 1991). Node size in A2 indicates the citation of non-patent (generally scientific) references. 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. Tie color corresponds to tie age: green ties were formed in the prior year, blue ties in the 2nd through 4th prior year, and red ties were formed five years prior. All network diagrams were plotted in Pajek with a directed force algorithm (Batagelj and Mrvar 1998).

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. [5] 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 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. [6] Todd Guion, a

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

[6] 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

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.

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 2004 evidence). 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.

Returning to the Stanford-IBM connections, William Risk and Professor Gordon Kino described a much more conventional linkage process, namely, the movement of graduate

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that hope to encourage collaboration between chemistry, engineering, biological, and medical research. Pyare Khanna felt that Biocircuits failed because it was too early and the integration was too difficult. Only now are some firms (such as Affymatrix) beginning to make money.

students from university labs to private firms.[7] This remains an important linkage between open science and proprietary technology, as argued by Dasgupta and David (1994). 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 for Stanford graduates appears to be the flip side of Professor Cohen's description below of non-local employment for MIT graduates. As such, the processes of local and non-local employment of graduates surely operate similarly across regions – when appropriate local firms are hiring, graduates are more likely to stay, and when they are not, or if the region lacks such firms, graduates emigrate. For example, William Risk stressed the importance of optics to a wide variety of industries and how the Valley provided a great diversity of technological applications and industrial opportunities. Even though Angel (1989) provides some evidence that Valley firms are more likely to hire local graduates than firms in other regions, categorizing these processes as Silicon Valley specific is mostly an expositional convenience, based upon our interview sampling and the economic conditions at the time.

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

[7] 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 and given that the Stanford-IBM inventors knew each other well and corroborated (Kozlovsky corroborated the processes described here via a phone interview), we report from Kino and Risk. Given that a very similar process occurred twice over two years, it would appear to be a robust and frequent occurrence.

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 figures A9 and A10, 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.[8] Like Campbell Scott in the Valley, these Boston

[8] 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.

inventors overcame legal, managerial, and strategic obstacles to collaboration across organizational boundaries.

Koning and Kaufman both reported switching job functions within DEC several times [9], 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 Associates (a small, high risk software firm in the same region), and Perlman left DEC for a local (but telecommuting) position with Novell.[10]

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 (Angel 1989). 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. This will be reflected in a decreased rate of patenting and smaller components.

[9] 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 Bostonian).
[10] 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.

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 (figures A7 and A8) 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 the figures). This memory only serves to bolster Umatoy's earlier conjecture 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 figures A5 and A6), Komag, Exxon Enterprises, Canadian Research Corporation, and a variety of startups. Most became CEOs, CTOs or Chief Scientists, and they often left with the core technology they had invented at PARC. He could not remember any colleagues who left for an established firm, mainly because the 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,[11] Charles Kaufman observed two corollary points: DEC was not hiring due to its economic concerns [12] and leaving was considered "kind of 'traitorous.'" In fact, he noted that DEC had an explicit policy that employees who left were not to be rehired, and he recalled few people leaving before formal layoffs began in 1991. [13]

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

[11] 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.

[12] 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.

[13] 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.

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 Raychem, a large and established firm in polymer chemistry, 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 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 - with approval, given that his friend was the founder, but supplying all his own materials, and not interacting with the employees or with access to proprietary information. He also worked in the lab of a supportive professor at USF. He then read about an analytic technique to measure the effectiveness of his material, developed by Channing Robertson at Stanford. He contacted Prof. Robertson in 1986 and asked for help. Robertson replied that he would leave the decision to his best graduate student, Seth Darst (now a professor at Rockefeller University). Darst agreed to help, but as a typical graduate student, didn't begin working until midnight. Undeterred, Froix would sit on the stairs next to the lab from 6:00 pm, when the building was locked, until Darst arrived many hours later. The collaboration worked and Froix perfected his invention. [14] 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. [15] According to Boston Scientific's Chief Technology Officer, the technology has become an important part of the firm's product portfolio (Cohen 2003). Froix is now working with a molecular biologist on tissue generation with stem cells.

As can be seen in figures A3 and A4, 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,

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

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

but Boston inventors may also have had after hours access to firm, and university laboratories or professors at MIT or Harvard that were 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 also had an oft-repeated story (told by the protagonist in Packard 1995), about the founders coming in on the weekend and finding the central lab supplies locked. They sought out a security guard, had the padlock cut, and ordered that lab supplies should never 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 and science cultures (wherever they might be) place creativity before financial and proprietary concerns.

Paul Koning expressed skepticism regarding such a generous flow of information or resources across collaborative linkages 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 within Boston, MIT graduates tended to take academic jobs outside of the 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. Finally, some firms patented reluctantly in order to control costs.

Whereas the IBM component emerged by 1987 to serve as the underlying foundation of the largest 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. [16] The immediate cause of this instability is dramatically illustrated in figures A9 and A10. Robert Stewart is the only inventor that integrates the three major sub-components at DEC. Stewart (2004) indicated that his integrating role arose from his popularity as a design reviewer across different DEC product lines. While these design reviews did not create the observed ties, they enabled Stewart and other technical leaders to know where the experts were located in the corporation. When Stewart or other smart colleagues had a question or problem that might benefit from collaboration, they knew who to contact. These contacts then resulted in the observed ties. The immediate cause of DEC's structural disintegration was the product life-cycle, however. DEC's lawyers generally filed all necessary patents the night before a product shipped. In this case, the upper and right ties had been created with the shipment of the Nautilus project in early January, 1986. The lower left tie had been one of many collaborations between Stewart and the R&D and networking groups and just happened to expire at the same time.

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

[16] 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.

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.

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. Given that Boston technology relies to a much greater extent upon university patents and published science (see illustration A20), its technical social networks might actually be more connected than the Valley's. On the other hand, Cohen also believed that academic interest in new ideas tended to shift from the successful proof of one concept to another, without sustaining 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.

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 complete resources of a large firm. Cohen's network component appears to fragment because his student collaborators left the Boston region and the because transferred technology went to small and insular medical device companies.

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.[17] 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. 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.[18]

[17] 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.
[18] Maya left GTE just prior to this change because he anticipated it; he would have stayed otherwise.

The tradeoffs between public science and private technology also influenced the collaborative linkages of Honeywell, the 6th largest connected component in the Boston network during the 86-90 time window. 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 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. [19] 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.

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

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.

If these policies resulted in fewer repeat collaborations, they should have made the DEC component larger but less robust. This might account for the persistent fragility in the firm's networks and 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.

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. 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. This Boston experience is in contrast to the movement of inventors with sellable skills on an external labor market in the Valley (Angel 1989).

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.

Discussion

As with all qualitative data, our presentation and analysis remain inseparable. Nonetheless, we wish to highlight three issues in our discussion. First, we are struck by the importance of institutions in the agglomeration of regional inventor networks. Universities and post doc programs play a catalytic role in the initial connections between components. Second, this institutional "glue" creates opportunities for inventors to forge new ties across technologies and firms. These new ties increase innovation in the region which, if successfully commercialized, increases wealth. This wealth can then be cycled back into institutions that increase inventor mobility, leading to a virtuous co-evolution of agglomeration and innovation. Finally, we will collect our impressions of the differences between Boston and the Valley and comment upon the Saxenian argument that the Valley is indeed more networked.

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 managers, organizations, and industries, than regions.

The only truly idiosyncratic stories in the Valley were the itinerant creativity of Michael Froix and the IBM post doc program. 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). When asked why IBM supported such a program, William Risk and John Campbell Scott provided a variety of reasons and motivations. 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.

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. Figures A9 through A12 illustrate the most dramatic examples of this process, the disintegration of the MIT/Foxboro/Dana-Farber component, Boston's largest component in 1985-1989. Its red 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 ties and completely fell apart. Given that this disintegration process would support the Saxenian arguments for Silicon Valley's more densely networked social structure, we tested the hypothesis that the Valley components were indeed more robust. Surprisingly, we found the opposite - paired comparisons across similarly ranked components indicate little difference, except that the second largest component is more robust in Boston (GTE) than in the Valley (and indeed, is by far the most robust of any component we analyzed).

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 in the reduced largest component 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 combinatorial 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 figures A9 and A10.

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 no 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 the 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 level 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 figures A13 and A14 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 a fundamental difference in the social structure of its collaborative network.

We also sought to understand whether Boston and the Valley reflected differences in information flows. We are struck by the bi-modal distribution of attitudes on the issue, mainly along professional lines, and independent of the region. Most of the inventors from both regions expressed 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. [20] Khanna also remained noncommittal about the classical argument for location in technologically dynamic regions, namely the availability of technical personnel (Angel 1989).

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

The inventors in the Boston region noted a similar tension between managers and engineers regarding the decision to share information. "At Digital," Kaufman explained, "management thought we had all these great secrets to conceal; the engineers knew that the value was in collaboration." Koning felt that the core of the issue could be found in the underlying multiplicity of purposes for patenting. For example, an inventor might wish to patent a technology as a means to block its development by others in order to monopolize its sale or licensing. Alternatively, an inventor might patent as a means to steer the technology's subsequent development by others via "licensing on very generous terms" in order to acquire a first mover/first to market advantage (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.

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, product life-cycles, 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. In the particular case of Silicon Valley vs. Boston, the former agglomerated first because Stanford graduates took employment at IBM Almaden Valley Labs and because IBM sponsored a post-doctoral program that seeded the Valley with IBM patent co-authors. In contrast, MIT graduates did not take employment at GTE, DEC, Data General, or Honeywell, and none of those firms sponsored collaborative programs like IBM.

Additional experiments: university-firm ties and early career inventor ties. Might do latter with an analysis of the shortcuts in the components, or the range of ties (ala Watts 1999) or a database wide measure of inventors vs. region. Newcomers vs. incumbents (Guimera et al. 2004). “Most job changes occur among recent entrants to the work force, and the probability of a worker changing jobs decreases rapidly with age and employment experience,” (Angel 1989).

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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 A27 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:

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.

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

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.

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.

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.

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.

Robert Stewart (interviewed because he was so central to the disintegration of DEC in 1990) earned an undergraduate and masters degree from MIT in electrical engineering. He took employment with DEC upon graduation and remained with the firm until its purchase by Compaq.

1Appendix 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.

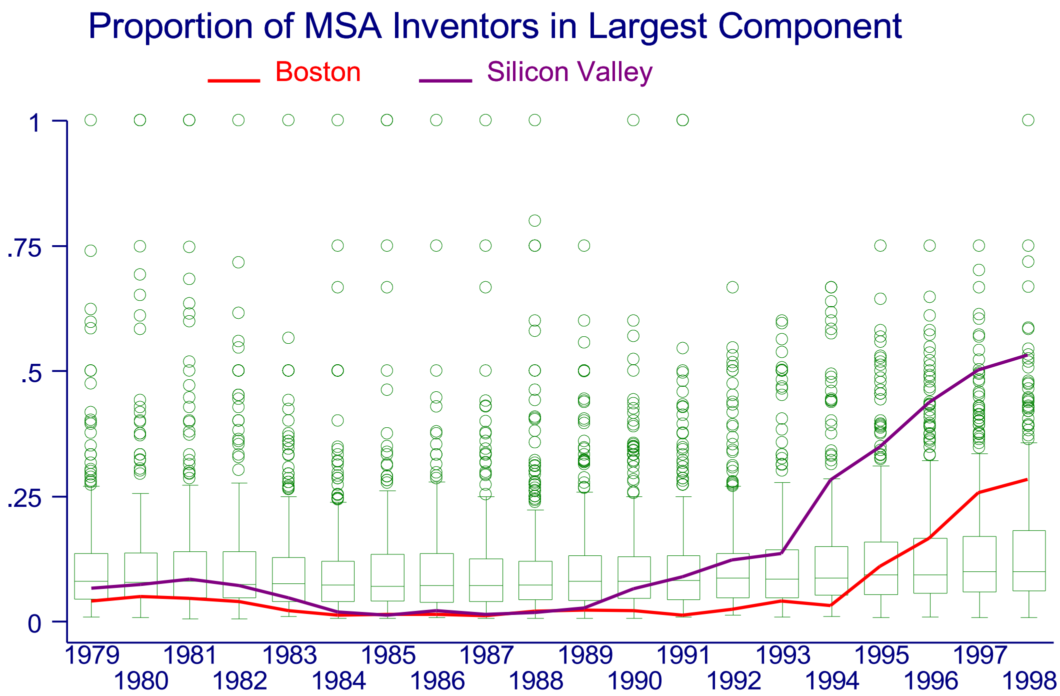

Figure 1: Box plots of relative size of largest connected component to entire network of patented inventor collaborations by U.S. Metropolitan Statistical Area (x axis indicates last year in five-year moving window).

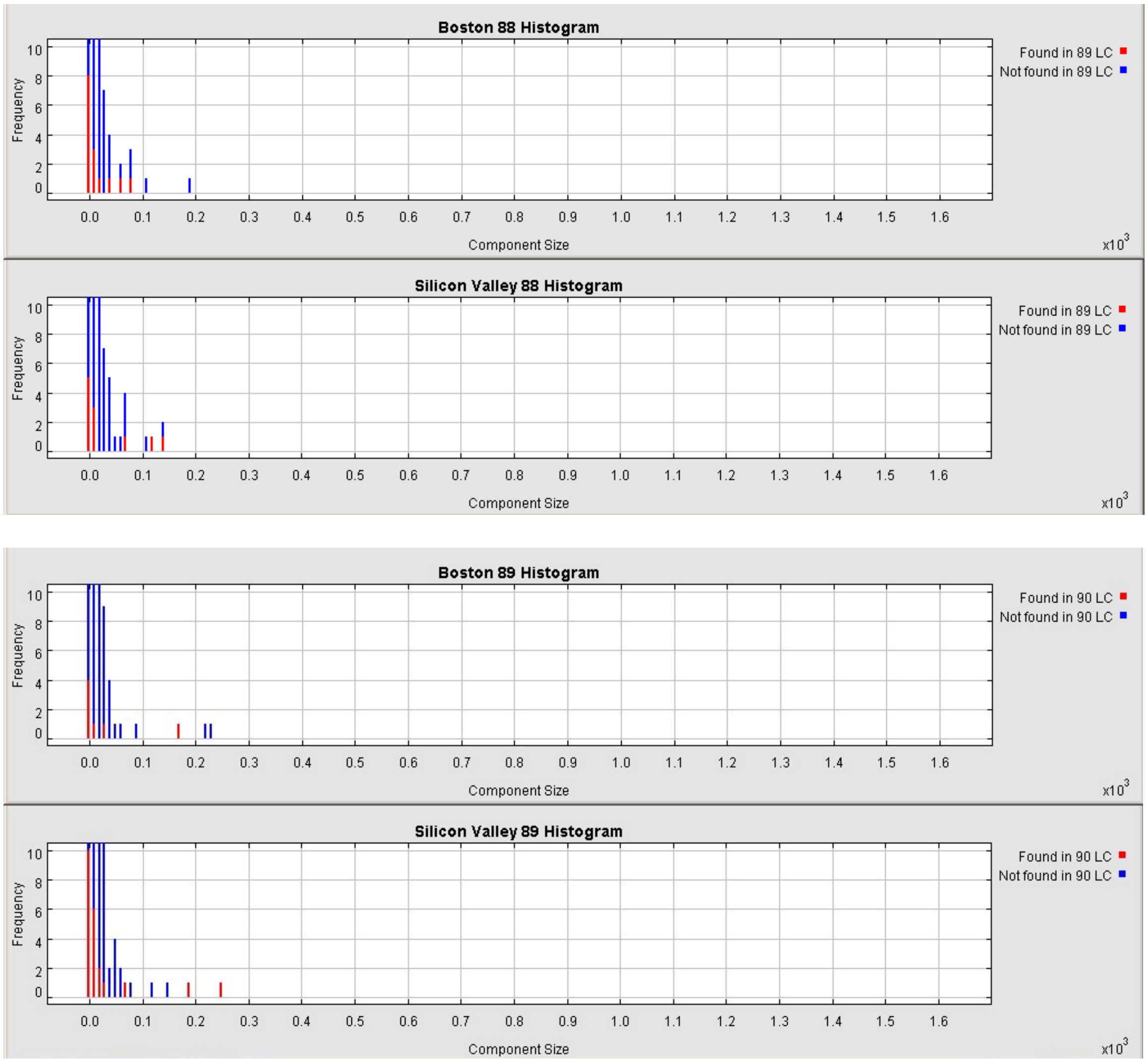

Figure 2: Time series of histograms of component size frequency of Boston, and Silicon Valley. The x-axis identifies the range of possible sizes for network components (demarcated into bins of 10 for readability), while the y-axis reflects, in blue, the number of connected components of a given (bin)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

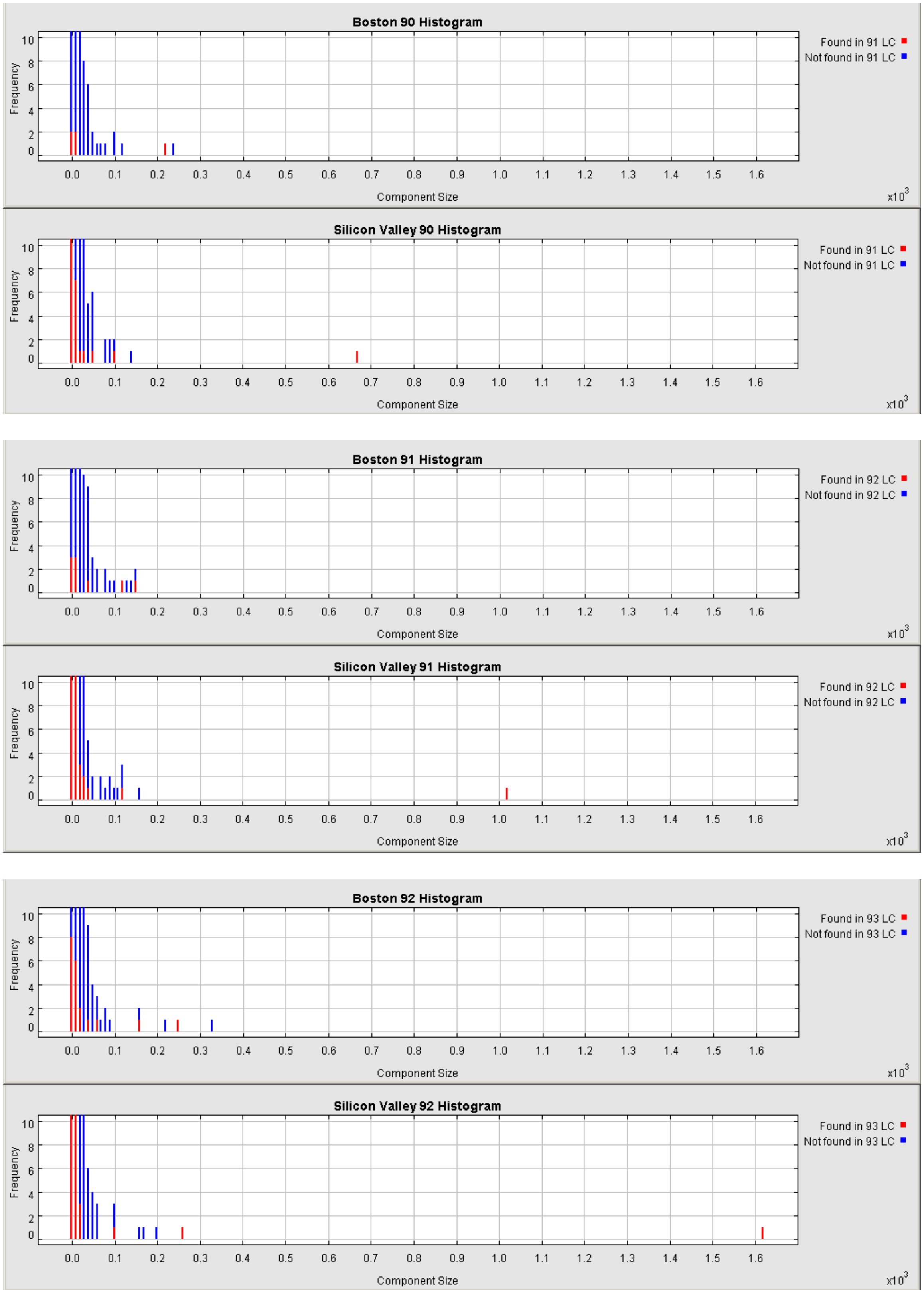

Figure 2 (continued): Time series of histograms of component size frequency for Boston, and Silicon Valley.

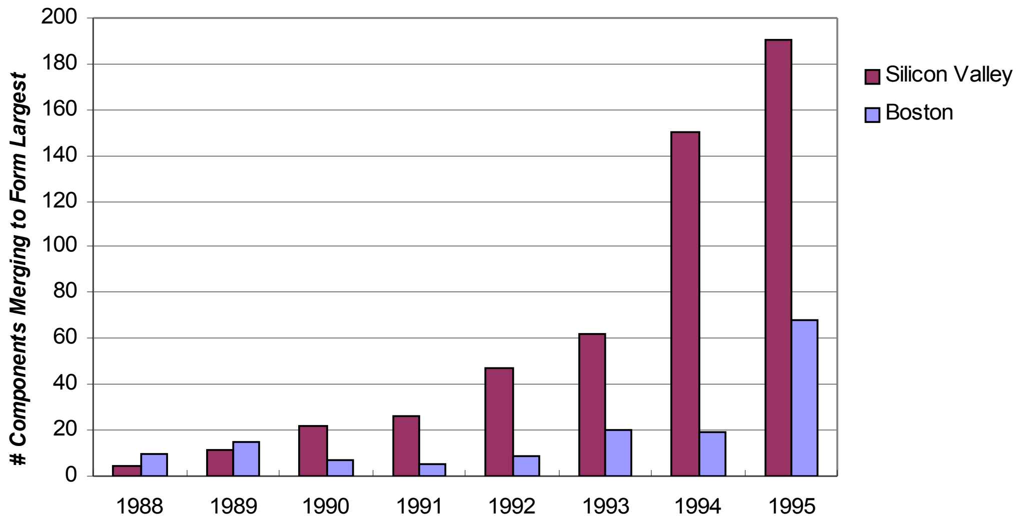

Figure 3: Illustration of how many components from previous year merged into each year's largest component. For example, in 1989, approximately 13 components from the Valley merged into the 1990 largest component, and approximately 16 components from Boston merged into the 1990 largest component. The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

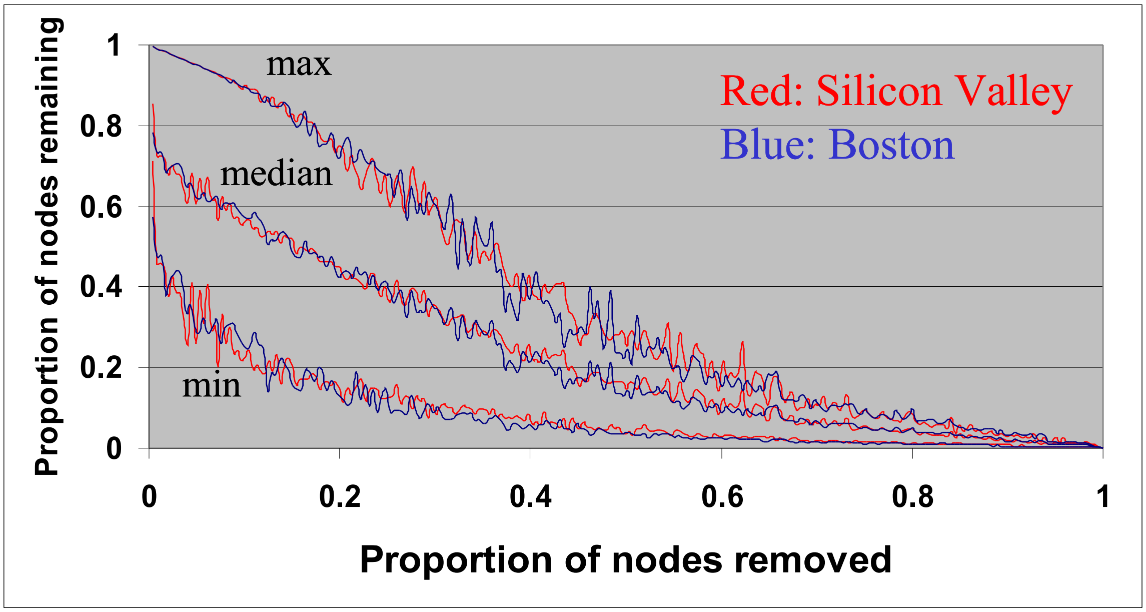

Figure 4: Size of component after removal of specified proportion of component's nodes, for Boston and Silicon Valley's 1st largest components in 1989. The y axis illustrates the proportion of nodes that remains connected in the largest resulting component, after a proportion of the original nodes have been removed. The x axis represents the proportion of original nodes that is removed.

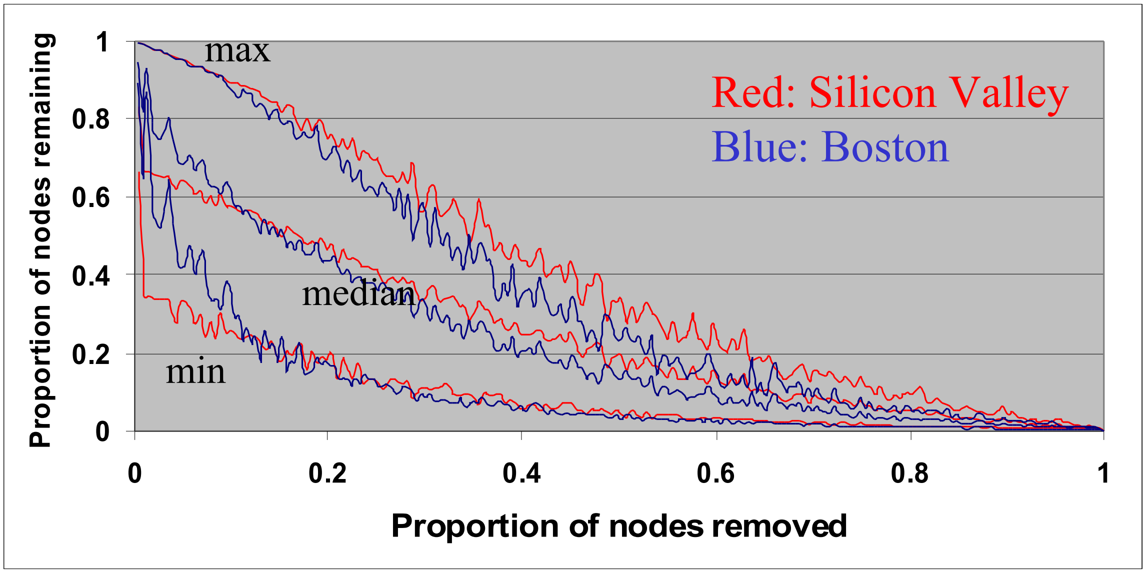

Figure 5: Size of component after removal of specified proportion of component's nodes, for Boston and Silicon Valley's 2nd largest components. The y axis illustrates the proportion of nodes that remains connected in the largest resulting component, after a proportion of the original nodes have been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