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Abstract: Tech clusters like Silicon Valley play a central role for modern innovation, business competitiveness, and economic performance. This paper reviews what constitutes a tech cluster, how they function internally, and the degree to which policy makers can purposefully foster them. We describe the growing influence of advanced technologies for businesses outside of traditional tech fields, the strains and backlash that tech clusters are experiencing, and emerging research questions for theory and empirical work.

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Introduction

Silicon Valley.

These two words evoke a complicated set of mental images. The Valley has been a lead character over the last fifty years in technological revolutions from the semiconductor to mobile internet. Its story includes large and colorful figures like William Shockley and Steve Jobs and Mark Zuckerberg, but also the ex post punching bags of failed ideas like Pets.com and fraudulent ones like Theranos. Today, business leaders located far away fret that "Silicon Valley is coming", a phrase Jamie Dimon made famous in JP Morgan Chase 2015's annual report. Uber and Airbnb showed how far reaching the innovations of tech clusters can be for even non-tradable services in distant cities (though Uber has yet to generate profits).

While Silicon Valley houses about 1% of the US population, and less than 0.04% of the world's population, its shadow looms large. Similarly, other prominent tech centers like Boston, New York, Washington DC, and Seattle have experienced exceptional opportunity and growth over the past couple decades, with problems such as extreme housing costs tending to be more of the consequence of "too much of a good thing" rather than the dire lack of opportunity felt in struggling cities. This paper reviews the tech cluster phenomenon and important questions for researchers. Despite the provocativeness of tech clusters, the literature is surprising sparse.

We first describe the spatial concentration of tech activity in the United States. Not surprisingly, our primary metrics are patents and venture capital (VC) funding, mirroring the empirical literature. We also note some interesting clues from emerging metrics on high-growth entrepreneurship and artificial intelligence (AI) researchers. The more rarified the technical input, the more concentrated it is in the data. Moreover, US tech development is becoming more spatially concentrated with time. This section discusses recent efforts to measure global clusters globally, which is much more sensitive to the yardstick chosen than domestic rankings.

We then organize our core discussion around three partially unanswered questions. The first question follows on our data description by asking how we might define a tech cluster—that is, what properties are required to be a tech cluster? This delineation has not been important to researchers and is harder than it first looks. While we do not resolve the issue, the discussion surfaces many interesting questions and issues about tech clusters.

We then ask how tech clusters function and whether they are different from traditional industrial clusters. Not surprisingly, knowledge spillovers are a powerful force in tech clusters, and recent work explores how knowledge transmits across firms situated in a tech cluster. Tech clusters also facilitate powerful scaling for the best designs when they combine modular product structures with high-velocity labor markets.

Our third question considers the roots of tech clusters and the mix of initial ingredients required for their formation. Top-down attempts to re-create Silicon Valley have mostly failed (Lerner, 2009).[1] Nevertheless, leading tech hubs have often emerged in new places following the

[1] Duranton (2011) considers policies toward building clusters, and Chatterji et al. (2014) review of policies towards clusters of innovation and entrepreneurship specifically.

emergence of general purpose technologies. Nicholas and Lee (2012) point out that Lowell, Cleveland, and Detroit can all lay claim for being the 'Silicon Valley' of their days. Today, the rapid growth of Toronto as an AI cluster points to limits of Silicon Valley's grip on this particular frontier and a future where many global cities rival each other. Tech clusters display strong agglomeration forces, but they are far from permanent.[2]

We conclude with thoughts about whether tech clusters are their high-water mark or likely to extend further. Our review focuses more on America than elsewhere, but much of what we describe in terms of the economics of tech clusters applies to other countries. The future of tech clusters is a top question for scholars of innovation and economic geography, one that deeply shapes all of our lives.

The Growing Concentration of Tech Activity

Innovative activity is substantially more concentrated than population. The most common measurements use patents or high-growth entrepreneurship supported by venture capital firms. With both approaches, researchers can avail themselves of detailed micro-data regarding individual inventions or funding transactions that allows flexibility to match to external firm-level data, follow individual inventors or entrepreneurs over time, and model networks or spillovers. The central liability with both approaches is that there are many forms of innovative activity not captured by either data strategy.[3]

Figure 1 shows the share of VC financing, patenting and population across leading metropolitan statistical areas (MSAs), MSAs not on the list, and non-metro areas. We order MSAs by their VC share. (This figure and the next one consider consolidated local areas such that, for example, we group San Jose, Oakland, etc. with San Francisco.)

Not surprisingly, larger MSAs hold a greater share of venture investment and patents, but the skewness is stark. The top 10 MSAs as ranked by venture investment hold 90% of VC activity and 47% of patenting, compared to just 25% of population. The far right of Figure 1 shows that patenting and especially VC investment are under-represented outside of tech hubs.[4]

These patterns also appear in employment data regarding tech frontiers. Using LinkedIn data, Gagne (2019) estimates that more than a third of AI researchers are located in the San Francisco Bay Area. This concentration is in part due to the strength of tech giants like Microsoft, IBM, and Google for the employment of AI researchers.

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[2] In this way, tech clusters follow the pattern of Duranton (2007, p197): "Small, innovation-driven shocks lead to the churning of industries across cities. Then, cities slowly grow or decline following net gains or losses of industries."
[3] Griliches (1990) and Hall et al. (2001) are the classic starting points for patent data. Carlino and Kerr (2015) discuss these data issues and provide recent references regarding data handling.
[4] Carlino et al. (2012) document the similar clustering of R&D laboratories. Carrincazeaux et al. (2001) measure that six French regions hold 75% of R&D workers compared to 45% of production. Audretsch and Feldman (1996), Feldman and Audretsch (1999), and Acs et al. (2002) are examples of work using new product announcements to measure the spatial allocation of inventive activity. Carlino and Kerr (2015) review this approach.

Figure 1: Spatial concentration of US venture capital and patenting

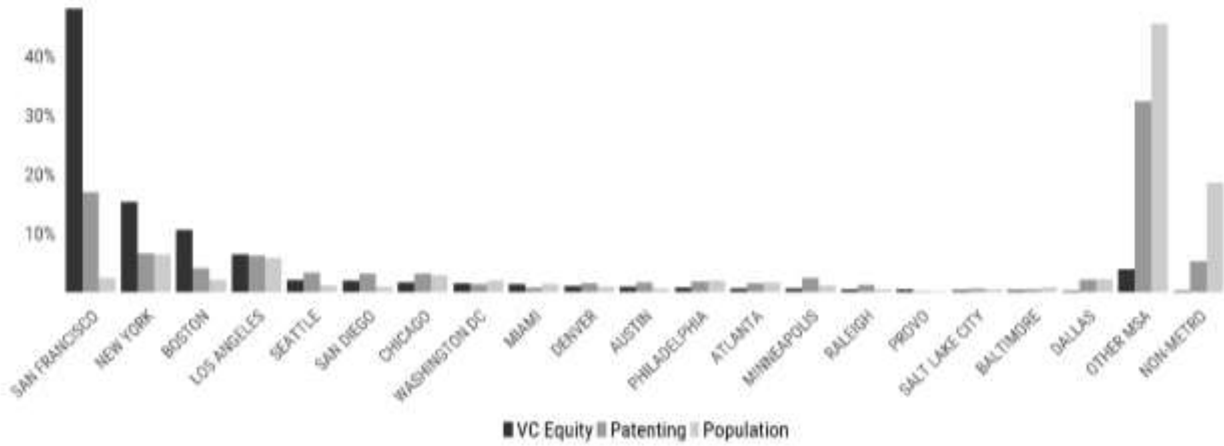
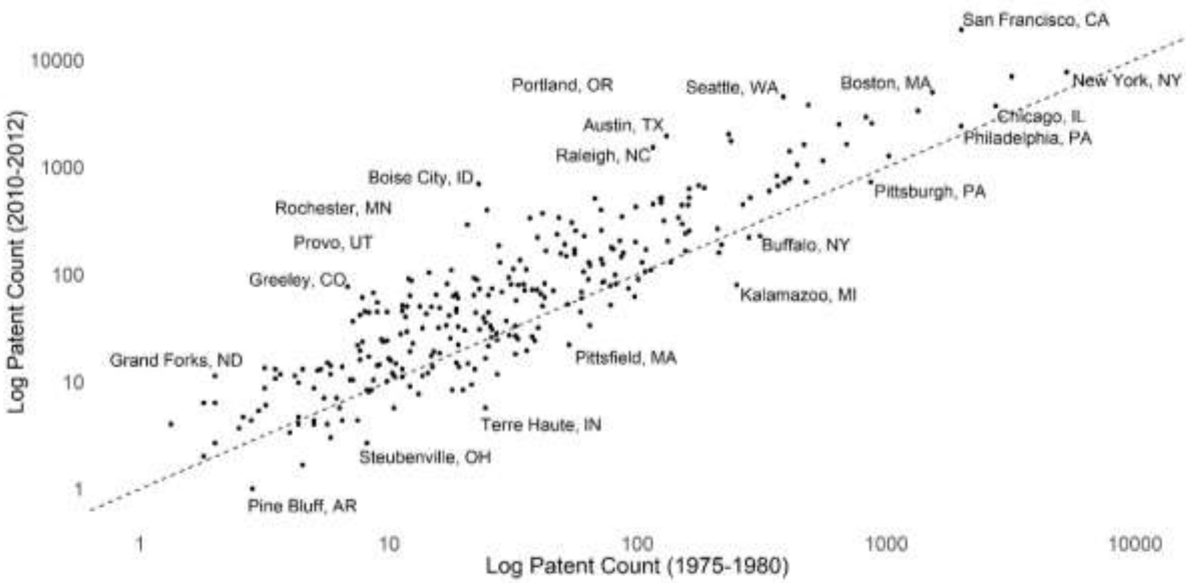


Figure 2 next compares the MSA-level growth in patenting (presented in annual terms) from 1975-1980 to 2010-2012. This figure employs USPTO patents granted through 2016, with both time windows being the application years for inventions. The axes are in log format and a 45-degree line is included.

Figure 2: Growth in annual patenting by MSA since 1975-1980



There has been an overall increase in patent grants since the late 1970s, with more cities being above the 45-degree line than below. Big cities show the most consistent increases, with smaller cities having greater variance. Boise City, ID, shows the greatest increase due mostly to Micron Semiconductor, but Austin (#3), Raleigh (#5), Seattle (#6) and San Francisco (#8) also feature among the top ten for growth. Consequentially, an Ellison and Glaeser (1997) index of patenting relative to population grows five-fold from an index value of 0.005 in the late 1970s to 0.025 after 2010. Kerr (2019) documents the important consequences from this rising spatial concentration for US invention.

Is the agglomeration of entrepreneurship as stark? The answer depends somewhat on the definition of entrepreneurship employed. Decker et al. (2014) document the long-term decline in U.S. entrepreneurship as measured through overall rates of business formation with Census Bureau data. By contrast, Guzman and Stern (2019) develop techniques to identify ex ante whether firms are targeting rapid growth (e.g., the name of the company, the startup's legal form of incorporation). Guzman and Stern (2019) find no evidence for the same decline in high-potential entrepreneurs as seen for overall business creation, and they note the most intense areas for entrepreneurial potential are places like Silicon Valley, Boston, and Austin (where they measure booms in local high-growth activity).

While it will take time to integrate these research findings, their combination suggests an interesting dynamic. Not only is high-growth entrepreneurship becoming more concentrated within tech centers, its stability relative to the broader declines of US business formation would suggest these favored places are becoming even more important in relative terms. Indeed, Guzman (2019) examines the migration of startups from their founding city to Silicon Valley. Higher-quality firms are more likely to migrate to the Valley, where they receive better knowledge spillovers and performance benefits.

We have stayed on safe ground for this review by focusing on US data, but an emerging frontier is to map out global hotspots. This combination of data across borders gets complicated fast, and Table 1 shows metrics do not always point in the same way. For VC investment, the last decade shows the remarkable rise of Chinese tech clusters. The top 10 global cities include Beijing, Shanghai and Shenzhen, plus London, in addition to six cities from the US. Looking instead at the post 2009 formation of unicorn start-ups (valued at $1 billion or more), the four non-US cities are similarly Beijing, Shanghai, and Hangzhou, plus London (Kerr 2018).

Table 1: Global Tech Clusters

Venture Capital Investment (Thomson One, 2009-2018)	Unicorn Startup Companies (CB Insights, 2009-2018)	Patent Cooperation Treaty Filings (WIPO, 2010-2015)
San Francisco	San Francisco	Tokyo-Yokohama
Beijing	Beijing	Shenzhen-Hong Kong
Shanghai	New York	San Francisco
New York	Los Angeles	Seoul
Boston	Shanghai	Osaka-Kobe-Kyoto
Los Angeles	Boston	San Diego
London	London	Beijing
Shenzhen	Seattle	Boston
San Diego	Hangzhou	Nagoya
Seattle	Chicago	Paris

While VC and patents provide similar pictures across US cities, globally this is not the case. In a World Intellectual Property Organization 2017 report (Bergquist et al. 2017) that aggregates over many patent offices, Tokyo-Yokohama holds twice the patent count to second place, Shenzhen-Hong Kong; the San Francisco Bay Area is third and Seoul is fourth. Moreover, the top 10 cities span three in Japan, three in America, two in China, and one each in Korea and France. And this is the tip of the iceberg: for frontiers like AI research, the leading roles of America and China are clear, but relative shares depend substantially on the yardstick employed and data source. Building a stronger foundation for these comparisons is an important ongoing task.

What is a Tech Cluster?

With a bit of data under our belt, we turn to how one can know a tech cluster when one sees it. Perhaps surprisingly, researchers have not needed to define formally a tech cluster. Most empirical analyses analyze the full distribution of states or cities, like the graphs in the prior section, which is helpful for getting a workable sample size.[5] Another route that skirts the issue is to conduct case studies or sub-city empirical analysis of an area like Silicon Valley or Cambridge, MA that few would dispute as a tech center (e.g., Saxenian 1994, Kenny 2000, Bresnahan and Gambardella 2001).

But perhaps the bigger challenges looming ahead are conceptual.

Advanced technology is pervasive in many sectors: As Jamie Dimon evokes the menace of Silicon Valley, is Wall Street and surrounding lower Manhattan a tech cluster? While a natural first reaction is "no, that's finance", Goldman Sachs in 2019 employs more engineers than the total combined workforces of LinkedIn and Twitter, and the iconic bank has been recently shedding traditional practices like dress codes to attract technical workers. Frontier quantitative hedge funds are at the bleeding edge of AI, and fintech advances may reshape huge parts of commerce. So maybe Gordon Gekko's Wall Street was not a tech cluster, but the Wall Street of 2030 might be. Using the framework of Duranton and Puga (2005), perhaps Wall Street will evolve from being a cluster specialized in a sector—financial services—into a cluster specializing in a function—(fin)tech?

These challenges are connected to how advanced technology and its leading firms are entering many parts of the economy through greater connectivity (e.g., Internet of Things), the rise of marketplaces (e.g., Airbnb, Farmers Business Network), competition jumping for consumers over categories (e.g., Apple Pay in financial services, Alphabet's Waymo in autonomous vehicles), and so forth. As robotics and cognitive automation technology advance, and as the shadow of an Amazon-like competitor—or maybe just Amazon everywhere—looms larger for previously protected segments, this ambiguity will grow.[6]

When does a city become or cease to be a tech cluster? Most cities aspire to be a tech cluster, with an astounding 238 cities going through the laborious hoops to enter Amazon's infamous HQ2 bidding process. Science parks spring up everywhere, and Wikipedia lists more than 25 efforts to brand a US location as "Silicon …". Our favorites are Silicon Peach (Atlanta) and Silicon Spuds (Idaho), whereas Silicon Prairie has at least four contenders. Much as Goldman

[5] Examples include Glaeser and Kerr (2009), Delgado et al. (2010), and Glaeser et al. (2015).
[6] Technology is becoming so pervasive that one can be tempted to resort to phrasings like "talent clusters" to focus on frontier activity by sector in human capital focused industries (e.g., Kerr 2019).

Sachs says it is today “a tech company”, the same branding aspiration applies to Silicon Anchor, Basin, Desert, Forest, Hill, Holler, Mountain, Shire and Surf (to name just a few US examples).[7]

Thus, should the methodology focus on effort and intention—such that one could be a very unsuccessful tech cluster—or should we select on outcomes? In the latter case, all tech clusters will have some measure of observable success when granted the title. Relatedly, are the measures context specific? Many label Bangalore a tech cluster, but much of its activity is substantially lower tech and labor intensive relative to tech clusters in advanced economies.

On this front, natural starting points for a formal definition are the traditional cluster properties of scale and linked activities. Local scale—encompassing absolute size of local activity and its spatial density—is straightforward and suggests that local aspirations are insufficient without results. How best to measure the linkages is more ambiguous, ranging from engineer mobility to technical knowledge flows to reliance on shared local inputs like a university for VC community. The next section considers initial work in this regard, and the linkage emphasized could influence whether the appropriate scale of a tech cluster is approximately Kendall Square near MIT, the larger Cambridge city, or the whole Boston metropolitan area. Bergquist et al. (2017) offer a nice discussion of their approach to these features when defining the patent clusters in Table 1.

Related, when does a tech cluster cease to be one? Few would select Detroit as a tech cluster today, but Detroit was the Silicon Valley of the first half of the 20th century. At some point, the auto industry matured and Detroit with it, and we would have taken away Detroit’s tech cluster badge. Should the mojo return with electric or autonomous vehicles, perhaps in 2030 we will declare Detroit a tech cluster again. Over its relatively short history, Silicon Valley has also experienced doldrums after technology waves crested, before the next major path emerged.

The Detroit example suggests that a focus on scale and linked activity alone is unsatisfying, as Detroit has plenty of both, but a tech cluster definition must have a frontier edge to it. For empirical work, we conjecture formal definitions could emerge where the cluster’s core output combines both frontier technical/inventive advances alongside meaningful economic impact on other sectors of the economy. Such a definition would put 18th century technology advances for cotton in Lowell, MA on par with AI in Toronto today, which seems conceptually useful. This definition could also have bite: e.g., it would suggest Wall Street is not a tech cluster if its AI advances remain focused on algorithmic trading, but the moniker would work if Wall Street becomes central to a blockchain future that reshapes the functioning of commerce.

The challenges are no less exciting for theorists. Jacobs (1969) showed how urban diversity and urbanization economies (i.e., agglomeration forces that cross industry boundaries) aid innovation through the recombination of ideas and experimentation.[8] Yet, competition for these valuable local ingredients also push up wages and rents. The seminal “nursery city” model of Duranton

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[7] See https://en.wikipedia.org/wiki/List_of_technology_centers#United_States. Many global examples of clusters named after Silicon Valley are also given.

[8] Jacobs (1969) stresses diversity as a source of urban dynamism. Henderson et al. (1995) provide evidence that Jacobs externalities are important for high-tech industries but not for mature sectors. See also Glaeser et al. (1992) and Lin (2011).

and Puga (2001) conceptualizes new industries emerging in large and diverse "nursery" cities. As industries mature and move from experimentation to scale, they no longer value the cross-fertilization and seek instead to maximize localization economies (i.e., agglomeration forces within a specific industry). The model portrays mature industries relocating to less expensive and more specialized cities.

This nursery city model provides a powerful tool for thinking about systems of cities (Henderson 1974), but our above discussion highlights two questions when applying to modern tech clusters. First, technology is becoming less of a segmented industry (i.e., PC manufacturer, shrink-wrapped software) and more ubiquitous and general purpose. There also exists a blurring of industry boundaries, especially as incumbents desperately seek to move out of stagnating industries and towards new profitable opportunities. How can theorists extend these models for this presence?

Second, the nursery city model fits many industrial experiences, such as the exodus of large-scale apparel manufacturing out of Manhattan over the last century (leaving the Garment District's name and key fashion designers behind). The nearby "Silicon Alley" in Manhattan's Flatiron district also previously held names "Toy District" and "Photo District" reflecting local activity. By contrast, autos went cradle to old age in Detroit, and other places like Lowell and Cleveland failed to renew themselves the way New York did.[9]

What explains these differing fates? The specialization of cities on function vs. industry lines is a promising starting hypothesis (Duranton and Puga 2005). Many models keep industry size second-order to city size, so that reallocation is more likely to happen at the industry level (Duranton and Puga 2001, Duranton 2007). By contrast, the historical examples also suggest a fast-growing industry may come to dominate a nursery city so quickly that the city ceases to specialize on a function (i.e., the breeding of new ideas) and instead specializes on an industry (e.g., autos), thereby pushing out the local industry diversity to other locations.[10]

A richer depiction of these interacting forces connects to many interesting literature strands. Helsley and Strange (2014) model that cities hold a (non-optimal) mix of co-agglomerated industries due to legacy location choices and persistence. Perhaps the larger city size of a London or Tokyo protects it from becoming too hyper-specialized around any one fast growing industry. Other work focuses on superstar cities and power couples seeking dual careers (e.g., Gyourko et al. 2013, Costa and Kahn 2000). Maybe New York's greatest lever for long-term sustainability today is that a couple can be a daring fintech entrepreneur and conservative healthcare CEO at the same time, so long as they can also pay $40,000 for their kid's pre-school.

[9] Glaeser (2005) describes how Boston has reinvented itself three times since its colonial days.

[10] The spatial equilibrium model (Glaeser 2008) also struggles with aspects of the distribution of entrepreneurship across cities (e.g., Chinitz 1969, Michelacci and Silva 2007, Glaeser et al. 2010). Behrens et al. (2014) and Davis and Dingel (2019) are recent contributions to the underpinning of a system of cities model, but as static models they are not designed to consider dynamics. Gabaix and Ioannides (2004) review work on the city size distribution.

Is a Tech Cluster Different from Other Clusters?

Clusters, of all shapes and sizes, arise due to the production advantages of local specialization combined with subsequent trade across locations. Marshall (1890) famously described three forces of interaction: customer-supplier interactions, labor market pooling, and knowledge spillovers. Economic research over the last two decades shows all three forces, along with natural advantages, are important for explaining industrial clusters, with the most recent research quantifying the heterogeneity across industries and dynamics over time (e.g., Ellison et al. 2010, Faggio et al. 2017). While researchers most often study the Marshallian forces in industrial settings, they apply, perhaps with even greater force, to tech clusters.[11]

Knowledge Spillovers

Knowledge spillovers are most deeply associated with tech clusters. As technology has become more powerful, the importance of these spillovers increases. Companies frequently seek early insights into upcoming possibilities, either through first access to codified knowledge (much like seeing the seminar version of a future NBER working paper) or through access to tacit knowledge that can't be so easily written down (the reactions of others in the seminar). Researchers often use patent citations to consider these questions.[12]

Kerr and Kominers (2015) explore these spillover mechanics using variation across tech industries and their patenting clusters. They model spillovers as localized within tech clusters, such that firms interact with their closest neighbors, but the costs of interaction prevent direct spillover benefits from more distant members of the cluster. For example, a firm in Oakland may have useful information for a startup in East Palo Alto, but the search and acquisition costs are too much to justify compared to those firms nearby. These conditions lead to localized zones of interaction, such that nearby interactions are direct, while those farther away happen through the underlying network of the cluster.[13]

The empirical work of Kerr and Kominers (2015) shows this through patent citations: firms are more likely to directly cite the work of their closest neighbors but indirectly cite those farther away in the cluster. Consequently, econometricians can compare the shapes and sizes of clusters

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[11] Each of Marshall's three forces has sub-variants, and Marshall outlined other factors that prompted agglomerations beyond the famous trilogy. Other formulations emphasize the higher-order functions like sharing and matching that occur within clusters (Duranton and Puga, 2004). Extensive literature reviews are captured by Duranton and Puga (2004), Rosenthal and Strange (2004), Behrens and Robert-Nicoud (2015), Combes and Gobillon (2015), and Duranton and Kerr (2018). Feldman (1994), Audretsch and Feldman (2004), Feldman and Kogler (2010), and Carlino and Kerr (2015) review the literature on agglomeration and innovation specifically.

[12] A well-known literature has considered the higher rate of patent citations within cities versus across them. See Jaffe et al. (1993), Thompson and Fox-Kean (2005), Thompson (2006), and Murata et al. (2014). Jaffe et al. (2000) evaluate the use of patent citations for studying knowledge transfer, and Breschi and Lissoni (2009) consider the role of inventor networks in these knowledge transfers. Audretsch and Feldman (1996) provide a classic account of the localization of R&D-based industries due to knowledge externalities. Olson and Olson (2003) document the very tight bands for collaborative interactions in particular. Waldinger (2012) by contrast finds no evidence for peer effects at local level.

[13] An interesting parallel to this setting is Arzaghi and Henderson (2008), who explore productivity spillovers among advertising agencies in Manhattan. Proximity to other agencies boosts productivity over the first half mile, but beneficial spillovers do not exist beyond a half-mile.

to learn about the technologies that sit behind them. Technologies with tight spillover lengths produce smaller and denser clusters. In this study, as well as others using broader sources of variation, knowledge spillovers are the most localized of agglomeration forces.[14]

Another promising line of work quantifies the different types of inventions in leading centers vs. outside. Carlino et al. (2007) and Berkes and Gaetani (2019) measure that patenting per capita across US cities mostly rises with higher density, with a 10% increase in density correlating with a 2% increase in intensity. Breaking the cities up into component districts, however, shows that patenting starts to decline in the densest places like downtown Boston or San Francisco. Instead, the peak is among districts with high but not too high density, like the Route 128 area around Boston or Silicon Valley on the West Coast.

Berkes and Gaetani (2019) further show that these frontier tech clusters foster atypical combinations of technologies that combine core elements seen in prior work with distinctly novel elements (e.g., Uzzi et al. 2013). This contrasts with the higher rates of internally focused innovation observed by Agrawal et al. (2010) in "company towns" where a single large firm dominates the local tech activity, such as an Eastman Kodak is Rochester, NY. Continued investigation into how the technologies developed in frontier clusters differ from other settings is important. It would be also interesting to identify when tech clusters can get too isolated from a potential customer group to understand latent needs. Michael Bloomberg is a very rich tech entrepreneur because he knew what his former colleagues on Wall Street were missing on their desks, which someone in California may have had a hard time figuring out.

Access to Specialized Labor

Tech clusters also rely on the labor market rationales for agglomeration. Strong clusters provide specialized workers insurance against the shocks befalling any one employer, deeper labor markets for better matching of particular skillsets with the best jobs, and often superior environments for investments in training by talented individuals without fear of later employer hold-up. These bread-and-butter features of labor pooling certainly persist in tech clusters and perhaps hold amplified importance.[15]

Access to specialized skills is a powerful magnet for tech clusters. In the 2016 American Community Survey, about 1.2% of the nation's college-educated workforce engaged in computer and digitally connected fields (Kerr 2019). This share was three times higher at 3.7% in the San Francisco, followed by Seattle-Tacoma (3.2%), Washington-Baltimore (3.1%), Raleigh-Durham (3.0%), Denver-Aurora (2.8%), Boston-Providence (2.4%) and Minneapolis-St. Paul (2.4%). Despite such relative abundance of sought-after skills, these labor markets have been exceptionally tight in recent years and exhibit very low unemployment rates. Thus, many

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[14] For example, Rosenthal and Strange (2001, 2003, 2008), Ellison et al. (2010), and Faggio et al. (2017). Singh and Marx (2013) demonstrate how political boundaries still matter for knowledge flows. Liang et al. (2019) stress local economic conditions (low commuting costs, skilled labor abundance) and technology features (localized knowledge spillovers, high startup costs) that are conductive to the decentralized emergence of science parks.

[15] Papers include Helsley and Strange (1990), Rotemberg and Saloner (2000), Berliant et al. (2006), Almazan et al. (2007), Freedman (2008), Gerlach et al. (2009), Sato and Thisse (2010), and Overman and Puga (2010).

businesses located in these talent clusters struggle to get the workers they seek, especially if they don't have a brand name like Apple or Netflix that attracts employees.

Firms also need to cautious about company doors that can operate in both directions. While bosses get excited about the top-notch employees and knowledge stocks at neighboring companies that could benefit their work, they are equally likely to have their employees and hard-won insights depart to rival organizations. Combes and Duranton (2006) model this tension, showing that single-minded pursuit of a position in the cluster is not always the best strategy. Matouschek and Robert-Nicoud (2005) highlight the role for firm-sponsored investments and firm-specific skills for why employers should think twice before jumping into the hot spot of their sector.[16]

These tensions stress an underappreciated aspect of tech clusters: they are an outcome of an equilibrium process. Thus, a free lunch rarely exists, and places with great spillover benefits usually bring very high prices for real estate and talent. This market pricing is true across cities and across small zones inside prominent clusters (e.g., Arzaghi and Henderson 2008). Indeed, abstracting from moving costs, escalating real estate prices can enhance the fidelity of the cluster, as only those who most benefit from the location are willing to pay astronomical rates. Similarly, Marshallian spillovers help and hurt firms. Few studies have explicitly modelled these tensions, and yet these insights shape our understanding in critical ways.

These labor tensions extend into employment law. Non-compete clauses in employment contracts limit the ability of a person to leave their employer and compete in the same segment (defined through the contract for a specified geographic region, industry/customer segment and time duration). Saxenian (1994) and Almeida and Kogut (1999) describe the high rates of inventor mobility in California, and Gilson (1999) proposes that Silicon Valley's dynamism should be attributed to the inability of local firms to enforce non-compete clauses.

Similar to patent duration, this policy choice is a calibration that may be too lax or binding. Employers may be more willing to invest in training if protected from the poaching of employees by competitors, but rigidities can also stifle the flow of ideas and the optimal matching of workers and firms. Marx et al. (2009) and Marx et al. (2015) study an interesting natural experiment when Michigan inadvertently changed its non-compete clauses such that inventor mobility declined by 8% or more. The impacts were particularly strong for those holding firm-specific knowledge or very narrow technical expertise, and consequently, many knowledge workers left to other states where enforcement was weaker. Hausman (2019) shows this impact extends in broader settings than the Michigan event.

Of course, firms can also seek extra-legal maneuvers. While many celebrate the high labor mobility and the lack of enforcement of non-compete clauses in the Valley, some local companies seek illegally to keep mobility in check. In the late 2000s, major tech employers

[16] Alcacer and Chung (2007, 2014) and Groysberg (2010), for example, consider these themes in the management literature.

entered into anti-poaching agreements with each other, later paying large fines to settle the cases.[17]

Industrial Organization and Scaling

The benefits that firms in tech industries gain from colocating depend upon local production techniques. Modularity is the method of making complex products or creating processes from smaller subsystems (modules) developed by a network of independent firms. Different suppliers are responsible for separate modules and follow "design rules" that ensure the modules work together (Baldwin and Clark 1997). This approach decentralizes innovation and may accelerate technical progress, since independent firms can focus on innovation to their specific components compared with the divided attention of vertically integrated firms.[18]

There is moreover a powerful connection between the labor markets of tech clusters and their industrial organization. Fallick et al. (2006) construct a theoretical model with modular production and local employee sourcing. They demonstrate how modularity allows for winner-take-all competition for the best design, with labor rapidly reallocating to the firm with the best design in order to scale it up for production. This benefit helps to overcome potential underinvestment in worker training due to rapid turnover in high-velocity labor markets. Empirically, Fallick et al. (2006) find substantially more mobility of college-educated males employed in Silicon Valley's computer industry compared to similar workers in the computer industry outside of California. Fairlee and Chatterji (2013) document a related phenomenon where start-up rates in tech clusters can decline in an exceptional growth period as the very tight labor markets push people to join scaling enterprises instead.

Recent research also explores the optimal firm size distribution for tech clusters. Agrawal et al. (2014) emphasize the importance of firm size diversity. They start with the need for large local firms to anchor the cluster; these firms produce ideas that do not fit well internally and thus get spun-out (e.g., Anton and Yao 1995; Agrawal and Cockburn 2003; Feldman 2003). A nearby large mass of small firms is also vital to lower entry barriers and stimulate specialized support services. Elements of this framework are present in accounts of Detroit in the early 1900s and Silicon Valley in the 1960s (e.g., Klepper 2010). Agrawal et al. (2014) find evidence for this model when looking at the innovative output of MSAs during the 1975-2000 period.[19]

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[17] Jeff John Roberts, "Tech Workers Will Get Average of $5,770 Under Final Anti-Poaching Settlement," Fortune, September 3, 2015, http://fortune.com/2015/09/03/koh-anti-poach-order/; and Kartikay Mehrohta, "Samsung, LG Accused of Silicon Valley Anti-Poaching Deal," Bloomberg, September 12, 2016, https://www.bloomberg.com/news/articles/2016-09-12/samsung-lg-accused-of-silicon-valley-anti-poaching-agreement.

[18] Sturgeon (2002) stresses that modular production allows colocated firms to use the benefits of spatial proximity to establish and manage global-scale production networks. Using evidence from case studies and interviews, Saxenian (1991) concludes that Silicon Valley–based computer system manufacturers became more efficient by spreading the costs and risks associated with the rapid changes in product designs and technologies by adopting modularity techniques. Related, Helsley and Strange (2002) model how a dense network of input suppliers lowers innovation costs, Helsley and Strange (2004) consider knowledge bartering in cities, and Strange et al. (2006) model how technical uncertainty can lead firms to agglomerate.

[19] Gompers et al. (2005) alternatively emphasize the degree to which young firms backed by VC are more likely to trace their founder's roots back to other young VC-backed firms versus large corporations.

Hellmann and Perotti (2011) provide another powerful theoretical contribution by modelling how tech clusters can help facilitate the generation, circulation, and completion of new ideas. Importantly, their work captures the tradeoffs of seeking to circulate and complete novel ideas within firms (e.g., greater protection) versus externally (e.g., greater idea circulation and matching). Their model predicts diverse organizational forms (internal ventures, spin-offs, and start-ups) coexisting and mutually reinforcing each other. An empirical analysis of these features, along with the acquisition of ideas into firms, is very promising for future research.

Immigration, Diversity and Tech Talent

Complementary to these discussions of the labor markets is the role of immigration and talent diversity. Indeed, classic early accounts of tech clusters by Saxenian (1994, 2002) and Florida (2005) emphasize how openness and tolerance in the community undergird the innovative productivity of the cluster.[20]

Tech clusters have become high-skilled immigration hubs. More than 60% of Silicon Valley's entrepreneurs are immigrants to America (Kerr and Kerr 2019), and the prominent CEOs of Alphabet, Microsoft, SpaceX/Tesla, and Uber are all foreign born. Even more important, much of the large innovative workforce of tech clusters comes from abroad. Immigrants accounted for an astounding two-thirds of San Jose's recent college-educated workforce in the 2013-2016 American Community Survey for information and communications technologies. Beyond this outlier, shares still exceed 40% in many tech clusters like New York, Los Angeles, and Seattle.

Kerr (2019) describes factors behind this reliance: e.g., STEM talent is quite transportable across countries, and the ranks of foreign talent looking for education and subsequent work opportunities in America in tech fields has been growing, especially from China and India. The US' employer-driven immigration system (e.g., H-1B program) also offers firms a substantial lever for using foreign talent in these STEM capacities. These programs help companies access scarce labor and keep workforces younger. Not surprisingly, a literature has quantified how growth in U.S. immigration can benefit these clusters and their major employer firms.[21]

Contrary to the growing evidence of a diversity premium for generating ideas, tech clusters have been frequently plagued with persistent challenges of a "bro" culture that disadvantages women and minorities. Despite high-profile tech leaders like Ginni Rometty, Marissa Mayer, and Sheryl Sandberg, women are under-represented and sometimes dramatically so (e.g., only 2-3% of VC funding goes to women entrepreneurs). African American participation is also terribly low, with recent gains in professional occupations like management consulting and investment banking not occurring in tech work (Gompers and Wang 2017).

The culture of tech clusters, beyond the "bro" boorishness, has been closely associated with the development of an audacious spirit, seeking to "dent the universe". While the tolerance for failure is often over-emphasized, the culture celebrates pursuing the big dream vs. sitting on the sidelines. One can also become a legend in the Valley for exceptional technical skills and

[20] Florida (2005) and Falck et al. (2009) also consider amenities as an attractive force for highly skilled people.
[21] See Hunt (2010), Kerr and Lincoln (2010), Kerr et al. (2015), Peri et al. (2015), and Doran et al. (2019). Nathan (2014, 2015) provides similar evidence on London.

engineering prowess, not just having made a fortune. If money is the key yardstick in leading finance centers, and connections and influence matter in political capitals, the tech ethos celebrates most the global innovation. As with all talent clusters, the ubiquity of this spirit in tech clusters serves as a beacon for others who aspire to achieve such goals.[22]

While commentators historically showered the tech culture with healthy doses of praise alongside concern, skepticism is mounting due to fake news, privacy concerns, and data security breaches. Critics are increasingly questioning the once-celebrated "move fast and break things" spirit, leading tech companies in 2019 scrambling to repair the trust.

Future Research Opportunities

Looking forward, research on tech clusters is immature and ready to expand in many ways. New employer-employee datasets allow us to quantify the creation and scaling of enterprises inside tech clusters. This can build upon administrative data, such as the Census Bureau's Longitudinal Employer Household Survey, combined via external links to patenting and VC data. Others will take advantage of private datasets like LinkedIn, which is almost a pseudo-Census of this industry. These analyses will help differentiate among the many theoretical channels for labor market pooling, ranging from greater matching to worker insurance.

Fine-tuned establishment data will also open up many new avenues of inquiry. Relatively few studies explore the internal choices within firms for how to place their many activities, which tradeoff proximity to sources of external insight with internal communication and alignment.[23] As the influence of tech grows, companies appear to be placing more key decisions makers and innovation personnel into tech clusters. The effectiveness and economic consequences of these choices will be important to study. For instance, Landier et al. (2009) quantify the greater likelihood of business leaders to close plants farther away from the corporate headquarters, which is worrisome given already widening regional gaps.

These types of data can refine our understanding of local spillovers in tech clusters from knowledge work to other industries. Moretti (2012) calculates that knowledge work creates five non-technical jobs for each knowledge worker, a local multiplier that is substantially higher than manufacturing. These generated jobs also pay better than similar work in other cities. Samila and Sorenson (2011) quantify how VC spills over into the creation of new jobs in local areas beyond those directly supported, and that these tend to be well-paid positions, but that the magnitude is overall modest in nature. The escalation of rents, however, also crowds out lower income individuals (Gyourko et al. 2013).[24]

Emerging research is also exploring how tech clusters shape the careers of individuals. Moretti (2019) finds that inventors moving to larger clusters experience increases in their patenting

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[22] Kerr et al. (2014) emphasize the experimental nature of entrepreneurship that aligns with parts of this ethos. Hofstede (2001) is a classic in the culture of workplaces.

[23] For example, Aarland et al. (2007), Davis and Henderson (2008), Tecu (2012), Alcacer and Delgado (2016), Lychagin et al. (2017), and Kerr (2018).

[24] Hsieh and Moretti (2019) estimate that housing constraints that limited the spatial reallocation of workers towards the most productive cities of New York and the San Francisco Bay area lowered US growth by 36% since the 1960s.

outcomes with an elasticity of 0.07. He further calculates that the special concentration of inventors as a whole boosts innovation by 11% compared to a scenario where all inventors spread out evenly over cities. Future work can extend this exciting and novel person-level perspective to see how cities shape the types of work created by inventors.

Universities are also important, but we have not yet worked out a comprehensive set of explanations as to why. Hausman (2012) documents how university innovation sparks local industry growth, and these spillovers can attenuate rapidly (e.g., Andersson et al. 2009, Kantor and Whalley 2014). Universities are also likely to be important simply as source of young, smart workers who have skillsets employers want. Marshall's account of the factors prompting agglomeration included the natural advantages of locations (e.g., natural harbors, coal mines). Strong universities, along with government-sponsored laboratories, are likely to be key (man-made) natural advantages for the tech clusters of tomorrow.[25]

Finally, the linkages across global tech centers deserve attention. Saxenian et al. (2002) and Saxenian (2006) describe how high-skilled migrants connect leading US and Asian tech centers, and a substantial share of patent inventor teams are today cross-border.[26] VC firms are especially well connected internationally (Balachandran and Hernandez 2019), and leading corporations maintain a string of labs across leading tech clusters. The internal practices these companies use to rotate workers across facilities and share knowledge (e.g., Choudhury 2016, 2017) will have a substantial impact on the broader integration of these clusters.[27]

Preconditions and Dynamics of Tech Clusters

An emerging frontier of research focuses on whether tech clusters can be created and the preconditions necessary. Nicholas and Lee (2012) and Lamoreaux et al. (2004) describe how US economic history shows a continual movement of the leading center for technology: for example, Lowell for cotton in the 1800s, Cleveland for electricity and then steel in the early 1900s, and Detroit for automobiles in the early-mid 1900s.

In a portrait of the origins of Silicon Valley, Nicholas and Lee (2012) note San Mateo County was a backwater for several decades from the 1890s. While it had several of the pre-conditions of a tech hub, it wasn't until the 1930s that the area began to be noticed for its work on transistors, vacuum tubes and microwaves, which helped draw in larger firms and enabled startups. The government's huge demand for electronics in World War II brought critical mass to the region, as the local population of tech engineers surged from 1000 to 10,000 in few years. Saxenian (1996) further depicts how the blank slate of the area allowed for new forms of work to emerge that reinforced and amplified this traction.

Other accounts similarly note the difficulties in predicting where leading clusters will take root. Klepper (2010, 2016) compares the roots of Silicon Valley to those of Detroit. Klepper emphasizes how high-tech clusters form through the spinoffs that happen around leading firms.

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[25] Berkes and Nencka (2019) show that the placement of a Carnegie library into a city in the decades around 1900 corresponded to a substantial growth in patenting relative to peer cities for the next 20 years.
[26] See Miguelez (2014), Branstetter et al. (2015), and Kerr and Kerr (2018).
[27] Nanda and Khanna (2012) also emphasize the degree to which time abroad can aid entrepreneurs when they return to less well-connected parts of their home country.

This outsized influence for anchor firms generates ample room for randomness, such as William Shockley's move to the San Francisco area to be near his ailing mother (with spinoffs from Shockley Semiconductors including Intel and AMD) or the early movements of Microsoft and Amazon to Seattle. Krugman (1991) emphasizes the role of historical accidents in explaining *where* clusters form. Though the stickiness of clusters is straightforward to explain, predicting the location of the next cluster might be impossible.

One research strand does capture the importance of breakthrough inventions (which are themselves often serendipitous). Zucker et al. (1998) show that the location of biotech industry follows upon the positioning of the star scientists in the field, and the surging prominence of Toronto for AI work traces to its local leadership in research for the topic. Duranton (2007) formalizes how random breakthroughs could lead to shifts in the leadership of cities for a tech field or industry, such as Saxenian's (1996) portrait of semiconductors migrating from Boston to Silicon Valley. Cities (especially big ones) gain some industries while losing others, such that cities will expand and shrink more slowly than the underlying industry migration.

Ganguli et al. (2019) demonstrate how the same breakthrough can often happen contemporaneously in two or more locations, and new research considers the factors that shape which location emerges the winner. Duran and Nanda (2019), for example, study the widespread experimentation during the late 1890s and early 1900s as local automobile assemblers learnt about the fit between this emerging industry and their city. The authors find a potential advantage for smaller cities that had the necessary conditions, such as a sufficient strength for local input suppliers. Despite having fewer entrants initially, the concentration of activity for automobiles began to coalesce in smaller cities – Cleveland, Indianapolis, St. Louis and Detroit – with Detroit being the ultimate winner by the late 1920s.

Duran and Nanda (2019) propose that the smaller city advantage may have been due to the higher physical proximity of relevant stakeholders, allowing for easier experimentation (e.g. rapid prototyping of new parts) and circulation of ideas (Hellmann and Perotti 2011). The smaller cities may have also raised the salience of the new technology above other segments competing for attention and supplier finance and fostered relational contracts. A potential implication is that policy makers should focus on how to increase the odds they are favored in the shakeout process for the set of emerging frontier technologies.

Conclusions

Are tech clusters at their high water mark? Or, will they strengthen going forward as advanced technologies become more essential for business? A simple of extrapolation of trend lines suggests greater spatial concentration looms on the horizon. Indeed, many policy proposal ranging from pushing massive basic R&D stimulus into the heartland (Gruber and Johnson 2019) to creating regionally capped visa allocations for skilled immigrants, start with the premise that policy makers need to step in.

Yet, many factors may naturally limit further spatial inequality. Doubling Silicon Valley's size (which is impossible on many geographic and political levels) would still only make it 2% of the US population. We are witnessing a major transformation of business to achieve appropriate positions in powerful tech hubs, but most workers and consumers will always be far away. Large companies will only pay the hefty prices of tech clusters for some key workers, instead investing to ensure that the firm transmits the important information effectively to others in the company. Rising nationalism and populism, along with disproportionate voice given to smaller states, speak to political brakes that also govern how big tech clusters can become.

Economists can play an important role in this future. While we cite many papers in this review, the "field" is actually rather under-sized compared to its importance. The number of trade economists must be an order of magnitude larger, for example, but surely tech hubs matter as much for the US knowledge economy in the 21st century as trade in physical goods does. Moreover, Apple and its global iPhone supply chain illustrate how intertwined these forces are. Just as tech hubs lead to spillovers across technological and industrial boundaries in the real economy, it is our bet that they themselves will spillover into other parts of economic inquiry.

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