Frontier workers, and the seedbeds of inequality and prosperity

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This paper examines the role of work at the cutting of technological change – frontier work – as a driver of prosperity and spatial income inequality. Using new methods and data, we analyze the geography and incomes of frontier workers from 1880 to 2019. Initially, frontier work is concentrated in a set of 'seedbed' locations, contributing to rising spatial inequality through powerful localized wage premiums. As technologies mature, the economic distinctiveness of frontier work diminishes, as ultimately happened to cities like Manchester and Detroit. Our work uncovers a plausible general origin story of the unfolding of spatial income inequality.

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Introduction

In March 1955, Shockley Semiconductors set up work in a converted Quonset hut at 391 South San Antonio Road in Mountain View California, an unassuming town in a region known mainly, if at all, for its orchards and naval air stations. Workers at Shockley were devoted both to innovation and manufacturing, at a time when "building a semiconductor device … was much an art as a science. Even for well-paid and highly sought-after circuit designers and engineers, there were few formal courses and little knowledge that was not best gained directly through a process of trial and error, supervised, however informally by someone who had already successfully built semiconductor devices. Operators would check a device's 'doneness' as they would a cake, looking at color and returning it to the furnace if it seemed necessary." (Berlin, 2005: 115). The spirit of experimentation persisted well into the 1970s, by which time Fairchild Semiconductor had spun off from Shockley and was employing thousands of workers in the Bay Area. This early work at the frontier of semiconductors ultimately spawned a vast tech agglomeration that has, for decades now, redefined the contours of regional prosperity and inequality.

Considering evidence across 120 years, this paper explores the role of such 'frontier' work in shaping interpersonal and interregional income inequality in the United States, as well as the geography of prosperity. Researchers have long explored the ways that technology generates new forms of work – jobs, occupations, industries – while also destroying some older work through automation and obsolescence. This paper is part of that broad effort. We define frontier work as a specific subset of new work. Frontier work, in our usage, is new work that is closely associated with applying, adapting, and implementing new technologies. Workers at Shockley, and later Fairchild, were frontier workers because they were transforming experimental ideas in physics into workable and valuable engines of economic growth.

Using full count and public use extracts of the Decennial Census and American Community Survey between 1880 and 2019, we apply new routines that allow us to identify and analyze the geography and incomes of workers engaged in frontier activities. We make three contributions to existing knowledge. The first is to demonstrate that, when it first emerges, frontier work is highly concentrated in subnational space, and these 'seedbeds' are often precursors of later agglomerations of related, high-wage activities. We trace this pattern for two major episodes: the second industrial revolution of the early 20th century, based on mechanical-fossil-electrical technologies; and the third, based on digital technologies, occurring in the late 20th and early 21st centuries. In both revolutions, initial concentrations of frontier workers have been associated with growing regional prosperity for decades into the future, seemingly driven by a cumulative localization feedback. This finding is in line with the broader literature that new work in the recent period is spatially concentrated. But by reaching back in time to a previous period of major technological change, and by focusing narrowly on a subset of new work, i.e. frontier activities, we are able to discern the spatial seedbed phenomenon, and to verify that it is not unique to the digital industrial revolution by reaching back in time to a previous period of major technological change.

A second contribution relates to prior findings that cities are the favored locations of new work, with urban size, education, and density offering predictive power (i.e. Bloom et al., 2021; Lin, 2011). Those studies only consider the recent period. By looking farther back in time, we add nuance to their conclusion, showing that many cities with these features in an earlier period were not resilient in attracting it in the recent technological revolution. Thus, mere density, size or the presence of prior high levels of human capital do not, alone, lead to the growth of new frontier work in an urban area in a subsequent technological revolution. There appear to be specific seedbed and agglomeration processes in waves of new technologies that do not occur in all pre-existing high-skilled urban centers, often generating dramatic changes in the landscape of skilled work and innovation centers (Lamoreaux et al., 2004).

A third contribution is to demonstrate that the growth of frontier work is associated with rises in both interpersonal and interregional income inequality. Frontier work creates new high-wage occupations, jobs, and industries, and does so in a highly spatially selective manner. Some seedbed locations become hubs of major growth in high-income employment, which fuel the expansion of income disparities between people and between places of the kind that has been observed in recent decades in the United States. We describe such relationships not only for the recent period, but also provide suggestive evidence of similar dynamics for the late nineteenth and early twentieth century.

For intuition, consider the textile-, coal- and steam-centered industrial revolution of the early 19th century. The technologies enabling this revolution destroyed much pre-existing skilled artisanal work. But they also generated entirely new categories of tasks and jobs, and these became concentrated in leading centers of technological innovation and industry, notably Manchester in Britain, Boston in the United States, and Liège and Ghent in Belgium (Bairoch, 1988). A similar story can be told regarding the second industrial revolution that began in the late 19th century and continued through the mid-20th century. At that time, highly skilled workers (as well as even larger concentration of unskilled laborers) in new and transformed occupations concentrated in Detroit, Cleveland, Chicago, and other prosperous industrial cities of the day (Klepper, 2002; Lamoreaux et al., 2004). Analogous concentrations of skills and wages can be observed among regions such as the San Francisco Bay Area, Boston, and Seattle, that have been central to key technologies of the recent third industrial revolution.

Building a conceptual framework

The present research is motivated by a conceptual framework that draws from three literatures: labor economics, economic geography, and economic history. Labor economists examine the relationship between technological change, skills and the wage distribution, considering skill bias and the supply of educated workers (Autor et al., 2006; Card & DiNardo, 2002; Tinbergen, 1974). Major waves of innovation in the late 19th and early 20th century, and then since the 1970s, were skill-biased, yielding new technologies that raised the relative demand and productivity of workers with greater than average educational attainment. In the mid-20th century, education systems then gradually caught up by increasing the supply of skills, first by raising high school, and then college attainment. The result was a rising and then falling of income inequality, in line with the race between labor demand from technological change and labor supply from changing educational output (Goldin & Katz, 2009).

Though these models are powerful, the empirical work they have motivated does not actually observe new skills associated with new technologies. Instead, researchers indirectly infer them from the educational attributes of people who occupy jobs (Fortin, 2006), or generic measures of work tasks like cognitive non-routineness (i.e. Acemoglu & Autor, 2011). While useful, such proxies are not especially precise, as is evident in the existence of major residual wage inequality (Acemoglu, 2002; Kim & Sakamoto, 2008).

Recent research responds in part to these concerns by more precisely identifying the links between technology and work. On the theory side, Acemoglu & Restrepo (2020) set up a framework that distinguishes substitution and destruction of work by new technologies from augmentation, growth or complementarity of new technologies to new work. In the empirical literature, there is a long tradition of searching for the substitution effect, as updated in recent results (Acemoglu & Restrepo, 2020; Webb, 2019). Lin (2011) pioneered recent empirical work on job creation, by tracing the historical emergence of new occupations that appear in the Dictionary of Occupational Titles. In the same work, he also found that such new work is overwhelmingly concentrated in large urban centers. Additional recent research on technology and job creation can be found in Bloom et al. (2021), Autor (2022), and Autor et al. (2022). The latter match information in patent texts to texts ('micro titles') that census examiners use to update occupational definitions. When these overlap, there is evidence of what we refer to as 'frontier work'. In addition, new work can emerge from expanding markets, where scale effects allow further development of the economy-wide division of labor. Autor (2022) finds that frontier work is increasingly polarized between high-skill high wage tasks, and low-skilled (mostly service) tasks and occupations, and is a source of the well-known phenomenon of wage polarization. Taking the lead from this work, the research in this paper is interested in a particular subset of new work: that which is linked, through complementarity or augmentation, to new technologies, and hence will tend to be highly skilled and highly paid.

Meanwhile, in urban and regional economics and economic geography, the discovery of interregional income divergence that began around 1980 was a surprise to a field whose theoretical models were based on explaining long-term convergence (Carlino & Mills, 1993; Drennan et al., 1996). At a state level, between 1880 and 1980, low-income American regions grew faster than initially richer ones (Barro et al., 1991). Since then, a durable divergence, or at least the cessation of convergence, has been detected at various scales, including states, counties, metropolitan areas, and commuting zones (Ganong & Shoag, 2017; Gaubert et al., 2021; Kemeny & Storper, 2020a; Manduca, 2019). Spatial inequality has emerged as a topic of interest not just in the United States, but also in setting research and policy agendas across a wide range of countries at different income levels (Iammarino et al., 2019; Kanbur & Venables, 2005; Leyshon, 2021; Martin, 2021).

It is widely agreed that a key proximate cause of the recent rise in spatial income disparities in the U.S. is the growing geographical concentration of college-educated workers (Diamond, 2016). The category of college-educated workers will largely incorporate our sub-category of frontier workers, as we shall see. There has been considerable research on why college-educated workers move to certain places. This literature emphasizes the allure of consumption amenities, housing, spillovers in production, experience effects, assortative matching, and risk-management by double-earner couples (Baum-Snow & Pavan, 2013; Ganong & Shoag, 2017; Moretti, 2012; Storper, 2018). Empirical accounts centered on these choices are, however, ill-equipped to explain – in the aggregate – how and why the ensemble of such locational attractors seems to have switched from dispersing skilled workers during the mid-20th century, when spatial economic inequality was declining. It also cannot explain why these workers have become more polarized across places since around 1980, when spatial inequality began to rise (Kemeny & Storper, 2020b).

Another strand of the literature concentrates on the geography of labor demand (Autor, 2019; Berger & Frey, 2016; Galbraith & Hale, 2014; Kemeny & Storper, 2020a). College educated workers may have clustered in certain dense urban areas after 1980 because, increasingly, that is where jobs that fit their skills became situated. A good candidate for a shock that increases these forces for geographical concentration of skilled work is the third industrial revolution, whose effects started to take hold in the 1980s, just when we start to observe the sharp uptick in the inequality between people and places.

Employing this line of thinking, it would be of interest to account for where such concentrations specifically originate – not just that there are such concentrations. Such an effort would be aimed at shedding light on the geographical 'origin story' behind larger historical periods in which earnings become spatially polarized. Beyond a few focused case studies of early successful places and some important early synthesis of these considerations (Storper & Walker, 1989), the literature does not have much to say on this point, making generalization impossible. And yet, we are now several decades into a process where highly educated workers have piled up in certain large, dense cities, earning considerably higher pay than their counterparts elsewhere.[4] The current preponderant role of 'superstar' cities in inter-regional divergence today did not happen overnight but developed incrementally over several decades (Kemeny et al., 2023). And despite voluminous studies on 'evolutionary' economic geography and on the role of institutions with respect to economic change (Bathelt & Glückler, 2014; Boschma & Martin, 2010; Essletzbichler & Rigby, 2007; Kedron et al., 2020), this work has shed much more light on diversification across related activities than on fundamental historical shifts in the spatial distribution of work and rewards (Henning, 2019). In this paper, we try to fill in some of this gap by examining whether new concentrations of skilled frontier workers in each major period of technological change 'seed' waves of inter-regional inequality and possibly of longer-term local prosperity for the fortunate places.

Though the literature has little to say about frontier workers' locational patterns, with the important exception of Lin (2011), it poses some of the same questions found in the wider literature on college educated workers. Our focus on frontier work, however, has the advantage of being linked more directly to new skills that accompany the early days of a major technological shock. As such, it may provide insights into the temporal pathways, geographical origins, and long-term geographical turbulence from different technology shocks, thus informing an historical perspective on technology and economic geography.

The literature offers some conjecture on these pathways. Innovators who create frontier work may congregate in specific locations because the right people are already there, such that both the geography and ongoing innovation are responses to pre-existing supply (Kelly et al., 2014, 2023). But

[4] There is now an emerging literature on the secondary inequality- and migration-effects of the concentration of highly skilled workers in large cities (e.g., Buchholz, 2022).

it is equally possible that the firms that either invent or early-adopt the technologies that drive new work agglomerate for other reasons, and then face a local labor supply challenge. To meet growing demand, they may train people to perform frontier work, and/or draw in suitably skilled individuals from elsewhere, as was certainly the case among key firms in the nascent Silicon Valley. The present research cannot resolve this chicken-and-egg issue. However, by investigating these processes within a long-run perspective, we can get one step closer to the possible origins of frontier work, its related effects on spatial income disparities, and its ultimate decline with respect to incidence, concentration, and wage premiums.

The time dynamic applies not just to labor but to technologies themselves. Historians studying the economic effects of science and technology consider some innovations to be more important than others. Technologies said to be disruptive, radical, or general-purpose are contrasted against more incremental innovations (Bresnahan & Trajtenberg, 1995; Mokyr, 1990; Perez, 2010; Rosenberg & Nathan, 1982; Schumpeter, 1943). Major new technologies are not introduced continuously; they tend to be bundled together at particular moments in time. This emergence sets off waves marked initially by a 'fallow' period, and later by a 'reaping' phase in which technologies become pervasive, intensively reshaping production and thereby the structure of employment and rewards (David, 1990; Lipsey et al., 2005). Rents from such innovations, as well as skill-biased wage effects should be strongest in such reaping phases. For some, major innovations might reach their point of maximum application to the economy (diffusion) just before they become routinized and their economic rents subside. All else equal, the wage premiums of frontier work might rise and subsequently decline with these technological waves, with rising phases of technological disruption linked to spatial concentration, and declines linked to deconcentration.

It is therefore preferable to examine not only the post-1980 round of rising spatial and interpersonal income disparities, but to reach as far back in time as possible. This allows us to consider whether bursts of technological creative destruction generate frontier work and both spatial and interpersonal inequality generally, or whether this phenomenon is specific to the digital industrial revolution from the 1970s onward. In this paper, we reach back to the period starting in 1880; we have a specific method for identifying frontier work; and we are concerned with its wage contributions to inequality, as well as its geographical concentration and deconcentration over this relatively long run period. This also makes it possible to draw contrasts between periods of rising inequality and the distinctive features of America's mid-20th century (1940-80) economic and geographical "great leveling" (Lindert & Williamson, 2016).

Data & Methods

In order to trace frontier work and its geography, we examine tens of million observations on individuals, drawn from U.S. Census Bureau population surveys spanning two major industrial epochs: the Second Industrial Revolution and its immediate aftermath (1880-1980) and the Third Industrial Revolution (1960-2019).

Core data

We use public-use population microdata from a series of Decennial Censuses and, more recently, from iterations of the American Community Survey, made available by IPUMS (Ruggles et al., 2022). For each year, we rely on the most complete available data, using full counts for the years 1880 to 1940; one percent Decennial/ACS extracts for 1950, 1970 and 2019; five percent samples for 1960, 1980, 1990, and 2000; and samples of the ACS for 2011 (2009-2011) and 2019 (2015-2019). These surveys report a wide range of individual and household characteristics, including basic demographics; geography; occupation; industry; and for the post-1930 period, incomes. Our sample is restricted to the working age population who do not reside in group quarters, are not in schooling at the time of the survey, and who have income to report.

Commuting zones

To describe the spatial evolution of the U.S. urban system, we use 1990-vintage commuting zone definitions from Tolbert and Sizer (1996), which delineate functionally integrated economic units on the basis of commuting flow data, yielding 726 units that cover the entirety of the lower 48 states. Determining the right unit of geographical analysis is challenging, and especially so given our long study period. Previous studies have used census regions and states (Barro et al., 1991; Drennan et al., 1996), counties (Gaubert et al., 2021; Higgins et al., 2006), and metropolitan areas (Giannone, 2017). Given our long study period, these geographical units provide different trade-offs with respect to coarseness, internal heterogeneity, and functional change over time. The commuting zones we use here provide the strongest balance with respect to these considerations.

Of course, definitions derived from commuting flows in 1990 will less effectively capture the relevant geographical scale earlier in time, given that trade costs have declined quite strongly over the study period; commuting zones mean something different today as compared to a time when people traveled by horseback and rail. In their favor, commuting zones can be constructed from counties, whose number and boundaries have changed only moderately over the study period. And while they may conflate multiple previously distinct labor markets from long ago, in most cases they contain an agglomeration formerly surrounded by undeveloped land, thereby limiting bias.

Commuting zones are not reported in Census data, hence we must assign individual respondents in the Census to them. To do so, we adapt an approach described by Dorn (2009), in which individuals are probabilistically matched to commuting zones based on the smallest identifiable geography in the Census. From 1960 on, individuals are matched to commuting zones based on their County Groups and Public-Use Microdata Areas (PUMAs). For the decades prior to 1960, we rely on consistent State Economic Areas (SEAs). SEAs are based on single counties, or groups of contiguous counties that share economic characteristics and lie within the same state. SEAs were originally defined in 1951 and were applied retroactively to the historical census data by IPUMS. We assign each of these basic geographies a probability of belonging to each commuting zone, based on the population fraction in that commuting zone. Many locations map directly onto a single commuting zone. For individuals in locations for which multiple commuting zones are possible, we replace each observation with a multiple, adjusted by their person weight, reflecting the number of potential commuting zone units to which each individual may belong.

Periodization

A conceptual starting point is that industrial revolutions generate a specific group of frontier workers that play a key role in advancing the technological revolution through their adaptation, extension and application of cutting-edge technology. Although historians lack consensus on the precise moments marking out industrial revolutions, there is a fair degree of agreement on the broad timeline.

Accordingly, we divide our long study period into two distinct periods, each broadly corresponding to an industrial revolution dominated by an ensemble of general-purpose technologies. The first such period spans 1880 to 1980; the second covers 1960 to 2019. Our periods are based on the times when key technologies come into being and most especially, when they reach their peak effects in terms of production, work, and transformation of the structure of the economy in terms of output and wages (Bresnahan & Trajtenberg, 1995; Freeman & Louçã, 2001; Mokyr, 1990; Perez, 2010). Despite overlapping across the decades from 1960 to 1980, we mostly treat these two revolutions separately within our analysis. In our final set of results, however, we do investigate the role of this transitional periods in restructuring spatial income patterns.

While industrial revolutions lack definite, discrete beginnings and endings, there is good reason to focus on the 1880s as a starting point of the second industrial revolution. Even though practical versions of the electrical dynamo were being introduced in the 1860s, it took decades until these and other key technologies became widely incorporated into production. The 1880s also coincides with the closing of the western American frontier, and the movement of populations that settled the cities and regions in the west. The inception phase of the third industrial revolution – when its economic effects were not yet very important – can be dated from the invention and refinement of the silicon chip, between 1954 and 1972, when Silicon Valley firms transformed the chip into a practical, cost-effective, consumer-facing innovations. While the 1950s and 1960s were still dominated economically by the manufacturing industries of the second industrial revolution, the post-1960 years were also the years in which the frontier work of the digital revolution began to emerge.

Identifying frontier workers

A frontier worker is not simply someone who holds a particular level of education or credential, nor someone who performs a generic kind of task. Consider that while some individuals with a given level of educational attainment may engage in frontier work, many will not. This will be true even for those with specific, narrowly defined qualifications – say a bachelor's degree in computer science – and particularly so, when we rely on coarse measures of qualifications such as years of education. Our approach is therefore to define frontier work at the intersection of occupations and industries. This choice relates most closely to recent papers investigating similar themes, and which identify jobs at the leading edge of technological change by focusing on patent texts and job definitions (Autor, 2019; Bloom et al., 2021) and newly introduced Census job titles (Lin, 2011).

For intuition on our approach, consider the example of workers that the Census defines as 'Computer Systems Analysts'. In recent decades, one would expect the average worker in this occupation to be involved in more leading-edge work when she is in industries that concentrate other high-sophistication activities. Concretely, such a worker will be more likely to operate at the technological frontier when laboring within the Computers and Related Equipment sector, as opposed to systems analysts that are employed in the industry called Metal Forgings and Stampings.

We manage the complexity of this revolution by starting from three basic principles. First, frontier occupations should be reasonably well concentrated in certain sectors. Second, they should be relatively skill intensive. Third, frontier occupations should be a leading indicator of the effects of a technological revolution, with such specialized work growing not just in value but also in quantity, as innovation penetrates new areas of the economy.

To operationalize these three principles for the second industrial revolution, we consider shares and counts of workers by occupation (OCC1950) and industry (IND1950) between 1880 and 1980. For this period we follow the logic of Moretti (2012) and define frontier industries to include all sectors within the broad category of manufacturing.[5] As our goal is to capture work with a heavy focus in the emerging sector and that involves a high level of skill and novelty, we focus on occupations with at least a 40 percent concentration in manufacturing, and where the occupation is classified as professional, managerial, or technical (OCC1950 0-100, 200-400). To ensure that we are tracking jobs at the frontier, we calculate the relative size distribution of employment in each occupation from 1880 to 1980 using occupation-specific *z*-scores. This provides a straightforward scale for measuring occupational growth trajectories across the revolution, whether increasing, decreasing, or stagnant, as a means of capturing changes in the importance of certain types of work in the economy.[6] We also further validated our measure to ensure that the occupational patterns of interest are not being distorted by the inconsistent reporting of these codes across IPUMS datasets.

For selected occupations, **Figure 1** provides examples of occupational growth curves from the second industrial revolution. The are two clear sets of occupational dynamics evident across the six panels. Skilled occupations including machinists, cabinetmakers and molders experienced their peaks in size early in the revolution and began to fall quickly between 1920 and 1940. The trends for skilled electro-mechanical occupations like designers, electrical engineers and industrial engineers are a mirror to these trajectories; these occupations start out with modest shares of total employment, but then grow quickly after around 1940. Using a hierarchical clustering procedure (Giorgino, 2009), we then extracted occupations that exhibit increasing growth curves over the second industrial revolution. In general, declining occupations include occupations that were being deskilled like boilermakers, cabinet makers and machinists, and late- and rapidly emerging occupations such as electrical, aeronautical, and industrial engineers.

After applying these criteria, for the second industrial revolution we arrive at 13 frontier occupations, which we list in **Table 1**. Our classification of frontier work includes science-focused

[5] Using the harmonized IPUMS industry codes of IND1950 300-500.

[6] It is also plausible that such work is growing in demand relative to the supply of qualified labor. This might complicate interpretation if, in our analysis, our main aim was to relate frontier work to occupation-level local wages. However, our analysis selects frontier work not only on growing employment shares but on other features as well; consequently many non-frontier occupations will be also growing. Further, our estimation strategy links early concentrations of frontier work to growth in average local incomes. Aggregation and gaps in time should minimize any mechanical links between higher demand for frontier work and regional wages.

occupations like chemists, a variety of engineers, designers, and financial occupations like purchasing agents and buyers. These occupations capture a range of work activities that were core to advancing manufacturing in general, as well as innovation within it.

For the third industrial revolution, we identify industries using an existing classification of high-technology activity from the Bureau of Labor Statistics (BLS) (Heckler, 2005). The approach, based on the North American Industry Classification System (NAICS), defines "high-tech" sectors as those with an unusually large presence of scientists, engineers, and technicians. Among several thresholds specified by the BLS, we adopt the most conservative definition, which considers a high-tech industry to be one in which scientists, engineers, and technicians jointly accounted for at least five times the all-industry average industry employment share, or at least 24.7 percent.

As in the previous revolution, our classification of frontier occupations in the third industrial revolution requires the satisfaction of three criteria: (1) found in the frontier (high-tech) sector; (2) skill-intensive; and (3) growing over time. Distinctively, however, key technologies of the third industrial revolution emerged from a relatively narrow set of industries linked to digital technologies, and they have a lighter direct employment footprint than did the second industrial revolution at its peak. The high-tech frontier sector has generated fewer direct jobs for the economy than was true for manufacturing, and skill-intensive jobs are not spread as evenly across sectors as was the case a half century ago. As such, we only require an occupation to be at least 15 percent concentrated in high-tech to be included in our analysis.

Figure 2 illustrates growth curves for selected occupations over the third industrial revolution, with points on the *x*-axis tracking the period 1960 to 2019. As in the previous period, there are evident differences in patterns of growth and decline, with occupations like computer software developers growing consistently in size, while occupations like electrical engineers contract. We observed a clear bifurcation between jobs such as Biological Scientists and Computer Software Developers growing with occupations such as Drafters and Industrial Engineers declining. The contrast between these occupational trajectories demonstrates the changing nature of frontier work between the second and third industrial revolutions. We list these industries alongside their associated high-tech occupations in **Table 2**.

In order to determine how our classification relates to other approaches in the literature, we compare our measure of frontier work to Lin's (2011) new work data. Comparing the share of workers employed in new work occupations in 2000 on the scale of commuting zones or PUMAs, we find correlations with our frontier measure of approximately 0.90. This confirms that we are capturing a highly related process to Lin.

Measuring the seedbeds of the frontier

Understanding how frontier work might contribute to later income differences across places requires that we measure how its geography unfolded in the early decades of the industrial revolution. Our goal is thus to measure the degree to which a commuting zone concentrated frontier work before these activities were widespread in the economy. We measure the degree to which a commuting zone is a seedbed for frontier work with the following equation:

$$SEED_{jt0} = \frac{(\sum_{i=0}^{n} FW_{jt} + \sum_{i=0}^{n} FW_{jt+1})}{(\sum_{i=0}^{n} W_{jt} + \sum_{i=0}^{n} W_{jt+1})} \tag{1}$$

where the seedbed measure *SEED* captures the percentage of workers (W) i who are engaged in frontier work (FW) in commuting zone *j* over the early decades of the revolution t_0, the seedbed phase. For the second industrial revolution, this period refers to the year of 1880 (t) and 1920 (t+1) and for the third, it is 1960 (t) and 1980 (t+1). This calculation thus produces a continuous measure of whether a commuting zone was a seedbed for newly emerging frontier work. For ease of interpretation, we convert this measure into standard units with a mean of zero and a standard deviation of one.

Results

The incomes and geographies of frontier workers

We begin by describing some of the distinguishing characteristics of frontier workers. For each revolution, **Table 3** contrasts frontier workers against all other workers in the analysis. In both periods, frontier workers represent relatively modest proportions of the overall labor force – less than two percent. Despite being few in number, their income levels are more than 1.5 times that of the average worker, they are more than twice as likely to hold a college-level education, and, as indicated by their disproportionate share in the 20 largest communities, they are more likely to live in big cities. The frontier category is thus small in size, but highly educated, remunerated, and metropolitan.

The regional geography of frontier work changes across the two revolutions. In the second industrial revolution, frontier workers were overrepresented in the Northeast and underrepresented in the South. This pattern persists to some degree into the third industrial revolution. Frontier workers have, however, become substantially more likely to live in the West and less likely to be located in the Midwest. These changes point to the ascendancy in recent decades of west-coast cities over the traditional US industrial belt.

To examine the specific places in which frontier work has tended to emerge, **Table 4** presents the seedbed measures and income positions of the 40 largest regions across the two revolutions. The most intensively frontier cities in the early, seedbed phases (1880-1920) of the second industrial revolution included the Northeastern and Midwestern metropolises of Detroit, New York, Philadelphia, and Youngstown. Cities in northeastern states such as Buffalo, Pittsburgh, and Cleveland also ranked high. Across the period from 1940 to 1960, these urban regions mostly either maintained high income positions or they further climbed in income rank relative to other regions. Larger cities with a weaker hold on the frontier components of the second industrial revolution such as Atlanta, New Orleans and Scranton, either failed to progress into the top 100 urban regions in terms of income, or had even fallen down the income hierarchy of places.

The third industrial revolution has a somewhat different geography. Sunbelt cities are well represented in terms of frontier work, income position, and population size. Despite still ranking high in income in 1980, regions like Detroit, Buffalo, and Cleveland all declined in income rank over the following 30 years. Of the larger regions, those that improved their position – San Jose, Boston, San Diego, San Francisco, Denver – all score high as frontier seedbeds. These patterns point to the development of seedbeds of frontier work, early in an industrial revolution, as a potentially important precursor to maintaining or improving high average levels of income.

To provide more texture to these transitions, we map the geographies of frontier work and manufacturing in the seedbed phase in **Figure 3**, as well as the later distribution of incomes. These patterns confirm our earlier findings in showing frontier work to be highly concentrated in the Northeast-Midwest industrial corridor, as well in certain Mountain and Pacific regions. This westward concentration is a sharp divergence from the manufacturing sector as whole, which was more strongly concentrated in the industrial regions of the South, particularly in Virginia, North Carolina and Tennessee, as well as more indiscriminately throughout the Northeast. We therefore observe two deep points about the geography of manufacturing: whether in terms of employment overall, or solely in its frontier, its concentration was uneven, situated primarily in newly urbanizing regions. The regions in which it concentrated, however, are differentiated on the basis of whether the work was or was not frontier in nature.

Panel C of **Figure 3** shows that the capturing of the frontier components of manufacturing work was associated with long-term income levels. Frontier work was more concentrated in the Northeast, Midwest, and the Pacific over the 1880-1920 period, and these regions also exhibited high income levels by 1960. These relationships can also be articulated through the correlation coefficients for commuting zones' 1960 income positions and their manufacturing concentration in the earlier 1880-1920 period. While the population-weighted correlation between early concentrations of frontier workers and later incomes is +0.65, it is only +0.38 for the concentration of more general manufacturing work. The seedbeds of frontier manufacturing work therefore presage high levels of income more than four decades into the future.

Figure 4 provides a comparable set of maps for the third industrial revolution and reveals several notable departures from the manufacturing era. Firstly, frontier workers are much more likely to be co-located with non-frontier workers in tech sectors, whereas in the second industrial revolution, frontier and non-frontier work in manufacturing tended to be located in different places. Another difference is that high-tech frontier workers were relatively dispersed early in the digital revolution. While frontier manufacturing work had a strong regional bias toward the Northeast-Midwestern corridor, digital frontier work initially emerged across many locations inside and outside of the dominant industrial regions. This implies that while many of the early seedbeds were to be found in newly urbanizing regions, there were also many possible origin points for the revolution.

The geography of incomes is also notable in this respect. By 2010, a small set of urban regions along the Northeastern seaboard, as well as in Chicago, California, Colorado and Texas came to hold a strong advantage over other urban places. Some of these places were represented among the high-income locations of the second industrial revolution, but others were not. Long-term income levels are also closely linked to early concentrations of frontier work and the broader concentration of the sector. Specifically, the population-weighted correlation between the 1960-1980 worker concentrations of commuting zones and their income positions in 2010 are +0.76 for frontier workers and +0.55 for the sector as a whole. The two revolutions are therefore similar in that their early geography, particularly of their frontier workers, is predictive of long-term income levels.

We can gain further insight on the geography of workers across the two revolutions through correlation and spatial autocorrelation statistics. First, across both periods, there are notable differences in the correlations of the local share of frontier and non-frontier workers. The population-weighted correlation between commuting zones' workforce shares of frontier manufacturing and overall manufacturing from 1880-1920 is 0.63. The analogous correlation over the 1960-1980 period – between the share of frontier and general tech and finance workers – is 0.76. This provides quantitative evidence of the greater tendency toward co-location over the third industrial revolution as compared to the second.

This greater tendency is even more notable considering the underlying shifts in the geography of employment over the twentieth century. In **Figures 3** and **4**, we present Moran's I statistics of spatial correlation based on the counts of all workers (reference) and for worker counts within manufacturing and tech. The Moran's I statistics for manufacturing workers are substantially higher than they are for the workers of the third industrial revolution. This pattern reflects the general spreading out of the US economy and its leading sectors. When taken with the unit-level correlations above, however, this confirms a simple but important point: the third industrial revolution has had a more dispersed spatial footprint than the second industrial revolution, but its frontier and non-frontier components tend to co-locate.

Linking seedbeds of frontier work to long-term income levels

We now explore whether early seedbeds of frontier work predict later levels of local incomes and the structure of employment. Using a panel model, we estimate variants of the following equation:

$$Y_{jt} = \beta_1 SEED_{jt0} + \beta_2 INDUSTRY_{jt0} + Z'_{jt} + T_t + u_{jt} \quad (2)$$

where, for commuting zone *j* in period *t, Y* represents one of three variables: the log of average annual earnings, the share of the local labor forces engaged in frontier work, or the local employment share in the broader frontier sector. Our main variable of interest $SEED$ (equation 1) captures the time-invariant local concentration of frontier workers in the formative years of the industrial revolution. To distinguish frontier workers from general industrial geography, the $INDUSTRY$ term refers to the local concentration of manufacturing or tech workers. Z' is a vector of CZ-specific time-varying characteristics, notably total population, the share of workers that have obtained at least a Bachelor's degree, and the local share of employment in either manufacturing or high-tech; *T* indicates a categorical time variable denoting the year of the observation, which ranges from 1940 to 1980 for the second industrial revolution, and from 1990 to 2019 for the third industrial revolution; and *u* is the standard disturbance term.

Table 5 presents our estimates based on equation 2, with the first three models presenting results for the 1940 to 1980 period. Model 1 assesses the relationship between our seedbed measure – the local share of workers employed in frontier manufacturing occupations in 1880 and 1920 – and average logged incomes across CZs over later decades. We observe that a one-standard deviation in the seedbed measure is associated with a 3.4 percent increase in annual earnings in 2015 dollars.

Although the historical frontier share has a strong positive association with income, general manufacturing is negatively associated with income. A standard deviation increase in 1880 to 1920 manufacturing is associated with a 0.8 percent decrease in average incomes, conditional on other local conditions. This indicates that capturing the frontier (rather than routine) components of manufacturing was associated with particularly positive long-term income benefits.

In Columns 2 and 3, we also observe that initial concentrations of manufacturing are predictive of later concentrations. Higher frontier and general manufacturing shares are both positively associated with later concentrations of those workers, but not in equal measure. Early concentrations in general manufacturing are predictive of later concentrations of manufacturing workers, while greater frontier seedbeds are associated with the later presence of frontier workers. This suggests that not only is there a degree of stickiness to the manufacturing sector, but its different areas of work – frontier versus more general manufacturing work – also exhibit independent persistence. Early concentrations of frontier workers are thus associated with sustained long-term elite positions in these industries.

For the third industrial revolution, we observe very similar patterns. The seedbeds of tech and finance are particularly strongly associated with higher incomes and later specialization in the frontier sector. General specialization in technology and finance is associated with later concentrations of technology workers, but less so for its frontier or higher earning components. One point of divergence that is worth noting is that technology and finance employment in general tends to be positively associated with later incomes, albeit without statistical significance. This may point to the skill-biased nature of the third industrial revolution, extending beyond 'tech' narrowly defined to include finance, health care and possibly entertainment and other high level business services – a wider sectoral arc of skilled effects than was the case during the era of the manufacturing revolution.

In any case, these results demonstrate that across both the second and the third industrial revolutions, early seedbeds of frontier work are predictive of later income levels and concentrations of those workers, decades later.

The changing effects of frontier seedbeds on incomes

Having established strong associations between seedbeds and later income levels, we conclude our analysis by exploring how these associations play out within the context of long-term spatial income inequality. **Figure 5** reports the evolution of two sets of values over time. Panel A describes the persistence of the association between our seedbed measures and income levels over the period from 1940 to 2019. To generate the seedbed coefficients for income in this panel, we use the following specification:

$$INC_{jt} = \beta_1 \left(SEED_{2IR_j} \, x \, YEAR_t\right) + \beta_1 \left(SEED_{3IR_j} \, x \, YEAR_t\right) + SEED_{2IR_j} + \beta_2 SEED_{3IR_j} + YEAR_t + u_{jt} \quad (3)$$

where we regress the natural log of income for commuting zone *j* in year *t* on our time-invariant seedbed measures (*SEED*). We test for time-varying associations by interacting the seedbed measures with time (*YEAR*). As cities like Boston and New York were catalyst locations in both industrial revolutions, we adjust for the correlation of seedbeds across industrial revolutions by modeling these associations within a single regression model.

The blue line in **Figure 5**, Panel A shows the income benefits associated with the seedbeds of the second industrial revolution, measured from 1880 to 1920. While we find that these associations are consistently positive and significantly different from zero, the blue line is trending downward from 1940. From approximately 1980 on, the association flattens out and remains mostly unchanged up to 2019. This decline captures the period over which the manufacturing industry further disperses as its agglomeration effects weaken.

The red line shows the same relationship but for the seedbeds of the third industrial revolution, measured from 1960 to 1980. Before the digital era, the income levels of these tech seedbeds are similar in size to what we observe for manufacturing seedbeds in the later stages of the second industrial revolution. After 1980, however, there is a very sharp rise in the income levels of the seedbeds of the third industrial revolution. These years are also the first in which the relative income levels of the more recent seedbeds clearly surpass the post-1930s peak relative income advantages of the seedbeds of the second industrial revolution. This reflects the fact that the associations between the seedbed measure and income levels are generally stronger across the third industrial revolution than at any point where observe incomes over the second. The greater magnitude of these associations may reflect the skill-biasedness of the technology and finance revolution, and its agglomeration in a more limited set of regions, all of which are expressed not only in the geographical piling up of the skilled, but in geographical wage gaps within occupational skill categories that are much bigger than in the past (Autor, 2019).

Panel B then documents the overall trend in spatial income inequality across our study period. Interregional income inequality in the United States was relatively high in 1940 and was on a largely downward trend until 1980. These patterns fit comparable results for β- and σ-convergence in Giannone (2017) and Kemeny and Storper (2020a), recent historical analyses of the urban wage premium (Butts et al., 2023), and are broadly comparable to somewhat shorter-run evidence using data from the Bureau of Economic Affairs' Regional Economic Accounts in Gaubert et al. (2021).

We observe a clear correlation between the historical trajectory of spatial income inequality in Figure 5 Panel B, and the seedbed effects described in Panel A. In those periods when the seedbed association is growing more strongly, spatial income inequality does as well. Similarly, over the periods for which we observe declines in spatial income inequality – from 1940 to 1980 – we detect weaker correlations between seedbeds and incomes. The most recent era of rising inequality coincides with the period over which the seedbeds of the third industrial revolution become dominant. In combination, these graphs point to spatial and temporal links between the position of seedbeds and general patterns of spatial income inequality.

The trajectory of spatial income disparities in this figure are suggestive as to the sources of the widely debated puzzle of the turn to divergence since 1980, and to questions of what spurs reversals between epochs of rising and falling spatial inequality. The present paper cannot provide a definitive answer, but a plausible framework that follows from our review of the literature is that, in the late nineteenth and early twentieth century, the U.S. economy was intensively transformed in response to the suite of new, general- purpose technologies that are associated with the second industrial revolution. These technologies contributed to the emergence of cities, particularly in the Northeast-Midwest Manufacturing Belt, where frontier work was highly remunerated and spatially concentrated.

Then, approaching the mid-century, these technologies began to enter their maturation phase, with their potential for disruption largely exploited. With this came the exhaustion of rents from frontier work, because the skills required – though in many ways significant – were increasingly codified; as a consequence, the system of education and training began to expand supply to catch up with demand. The scaling up of manufacturing, along with new transportation infrastructure, also allowed its functions to be increasingly spatially separated, with value chains becoming stretched out over longer distances. These changes enabled the diffusion of all types of manufacturing work, enabling the mid-century economic development of the Sunbelt. In our income series, we thus observe both waning effects of the seedbeds of the second industrial revolution alongside a strong reduction of geographical income disparities.

Then, as argued in Kemeny and Storper (2020a), the advent and development of the semiconductor initiated a new, major technology shock. This produced new forms of highly paid frontier work in specific locales, setting off a new round of interpersonal and spatial income inequality that continues up to the present. We recognize, of course, that technology shocks are only one of several important forces that have recently contributed to spatial income disparities, including exposure to globalization, and major regulatory changes, just as in the past, specific shocks such as the Great Depression also exerted their own unanticipated effects (Garrett & Wheelock, 2006). While we cannot deeply explore all of the many dimensions of this framework or of the related history, in this paper we shed light on a potentially key element of it: the incomes and geographies of frontier workers.

Discussion: the historical perspective on spatial inequality

As this paper is explicitly framed using an historical perspective on inequalities, technological change, and work, in this conclusion we offer some suggestions for additional research to extend and deepen our contribution to historical analysis in economic geography and inequality studies.

While a growing body of research highlights the potential significance of individuals engaged in new work linked to new technologies, ours is among the first to investigate this idea in a long-run context of geographical income disparities. As in Kemeny et al. (2022), though from the perspective of the labor market rather than patents, patterns are consistent with a significant role for major, disruptive technological changes in regulating inequality. We have investigated the channel of frontier work, and the locations and incomes of frontier workers. In particular, their concentration in early periods may spur wider inequality, while their later dispersal could be among the major forces pushing for convergence. In the early part of an unfolding industrial revolution, there is spatial concentration or "seeding" of the frontier work through which the emerging technologies are invented, adapted, and implemented. These locations are not necessarily those of previous industrial revolutions, because technological disruption can undermine previous agglomeration economies, opening a "window of locational opportunity" (Scott & Storper, 2003), as for example how Silicon Valley became the center of the digital revolution, and not the previous geographical center of electrical engineering on the US East Coast.

As a major technological revolution advances, however, agglomeration economies lock in a set of favored locations. Certain locations endowed with seedbeds of frontier work advance as centers of new industry with particularly high incomes accruing due to rent-sharing and skill-scarcity. When agglomeration effects are at their strongest during the peak of the industrial revolution, this results in a reconfiguration of the prevailing patterns of spatial inequality.

Our historical analysis provides evidence that this process may have occurred over two industrial revolutions. We observe clear correspondence in the decline and rise of spatial inequality, with the maturation of one industrial epoch and emergence of another. Examination of the spatial income dynamics of the emergence of the second industrial is a clear but challenging next step. As the industrial seedbeds of the late nineteenth and early twentieth century began to root, did spatial income inequality accelerate as it has in the post-1980 period? Answering this question will raise significant challenges because, efforts to do so will need to contend with the scarcity of spatial income data before 1940. They would also need to address how to weigh the co-evolution of the second industrial revolution with the expanding footprint of the US urban system.

The third industrial revolution has already shown certain cyclical similarities with the mechanical-manufacturing revolution, in terms of inequality and the development of initial seedbeds of frontier work in the early years. Geographical income disparities in the United States have risen continuously since around 1980, coinciding with the initial period in which frontier work remains highly geographically concentrated. An important question is whether today's high levels of spatial inequality will attenuate at some point in the future, with an eventual deconcentration of high-tech and frontier activity on the same scale as what occurred following the maturation of the mechanical-manufacturing economy.

We cannot know whether the spreading out of high income work and inter-regional income convergence will play out as they did in the past, but there are at least two reasons to be doubtful. First, the manufacturing sector deconcentrated over a period in which the United States was still in a major urban transition, building out its urban system in the South and West. Today that transition has largely been completed. Enabled by reductions in trade costs, mature sectors have increasingly shifted activities overseas, to economies undergoing their own urban transitions, and cannot play the same developmental role that deconcentrating manufacturing did in the development of the US Sunbelt in the post-war period. The cheap land and housing that were available in California, Texas and Florida during the Great Leveling period of the mid-20th century are now gone, and housing supplies are increasingly inelastic, creating and entirely different environment for both population and firm sorting than in the past. Along these lines, firms in high-technology industries already locate much routine work abroad rather than within the United States. Second, unlike in the manufacturing age in the United States, high-technology industries have not generated large quantities of localized, lucrative jobs for less-skilled workers, as they did for laborers and machine operators in manufacturing in an earlier age. The absence of these localized effects in the digital economy can account, in part, for the long-term decline of US intergenerational mobility (Connor et al., 2024; Connor & Storper, 2020). Thus, globalization and the nature of high-tech work itself means that the decades ahead present a potentially very different picture to the later stages of the manufacturing revolution. If this is indeed the case, this would lead to the continuation of spatial income disparities within the United States, rather than another "great leveling" as occurred from 1940 to1980 (Lindert & Williamson, 2016).

Thinking more widely about new frontier work, there is a long-standing concern with 'labor aristocracies' and the people who comprise them. It was Engels, in 1857, who first called attention to the notion of a top 10-15 percent of wage earners, whom he believed could not be counted on to identify broadly with the rest of the working class. Since then, social science has been interested in the types of people who make up the top wage earners at any given time, as well as the level of intergenerational occupational-wage mobility into the top (Atkinson et al., 2009). Interestingly, there is little literature that precisely traces the origins of the work itself that ends up in the top 10-15 percent in the way that we note above. Ideally, a complete picture would enable us to identify the technological and spatial origins of highly rewarded work, as well as the process of matching people to such work, and the geography of such processes, over time. Our research should be viewed as an early step in this direction.

Frontier workers may constitute a relatively small part of the labor force at any given moment, but our work suggests that, through their spatial behaviors, they have outsized longer-term influence on certain economic and social processes. For example, in the vein of Piketty & Saez (2003), do a generation of frontier workers convert their high wages into capital, access to education, and thus affect intergenerational income hierarchies? Alternatively, how are certain types of frontier workers ultimately dethroned through the creative destruction process? And how does the combination of durability and change in frontier work affect the magnitude and timing of inequality episodes over long periods of time? Advances in data and computing power can give us new purchase on these questions (Connor et al., 2019; Connor & Storper, 2020; Kemeny & Storper, 2023; Leyk et al., 2020; Petralia et al., 2016; Rodríguez-Pose & von Berlepsch, 2014).

There is a geographical equivalent to the durability-timing-change question, relating to the possible path-dependent effects of building up labor elites, or conversely, the contingent and temporary nature of local economic development. Consider Silicon Valley in the early 1970s. The forms of frontier work we measure in this paper were incipient then, because the economic effects of the third industrial revolution were just beginning to be felt. Fifty years later, the growth of demand for such workers and their spatial concentration in the Bay Area and a few other regional economies have now generated a national pattern of urbanization marked by a sharp polarization: between populous and frontier-worker-dense metropolitan areas and the remainder of the system. What starts small may become big, and possibly durable. Understanding the origin stories of such processes is another key area of future work, and understanding technological change and frontier work over time and geographical space is a potentially important avenue within that field of investigation.

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Figures and tables

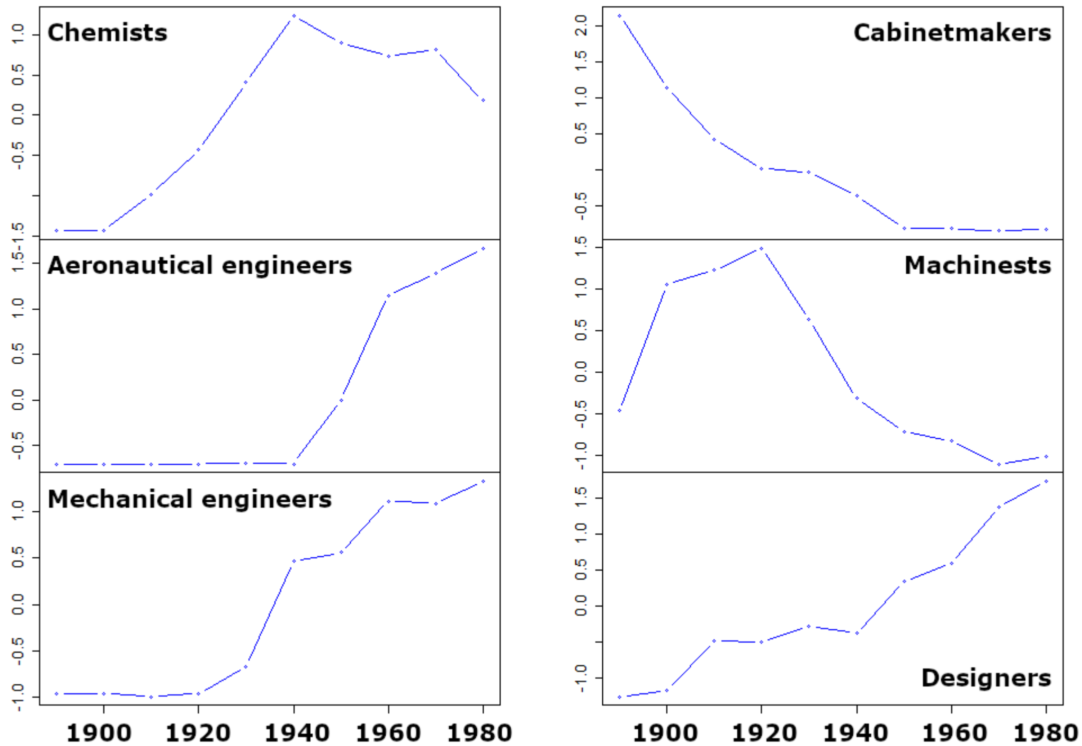

Figure 1. Time-series trajectories for selected occupations, 1880-1980
Notes: Graphs showing relative size trajectories of six occupations across the second industrial revolution. The x-axis (Time) is a decadal measuring beginning in Time 1 (1880) and ending in Time 10 (1980). Due to problems with the census in 1890, there is no observation for 1890. The y-axis shows an occupation-specific z-score the occupations share of the labor force in each time period. Occupations that grew in their relative contribution to the overall labor force have higher z-scores in later years.

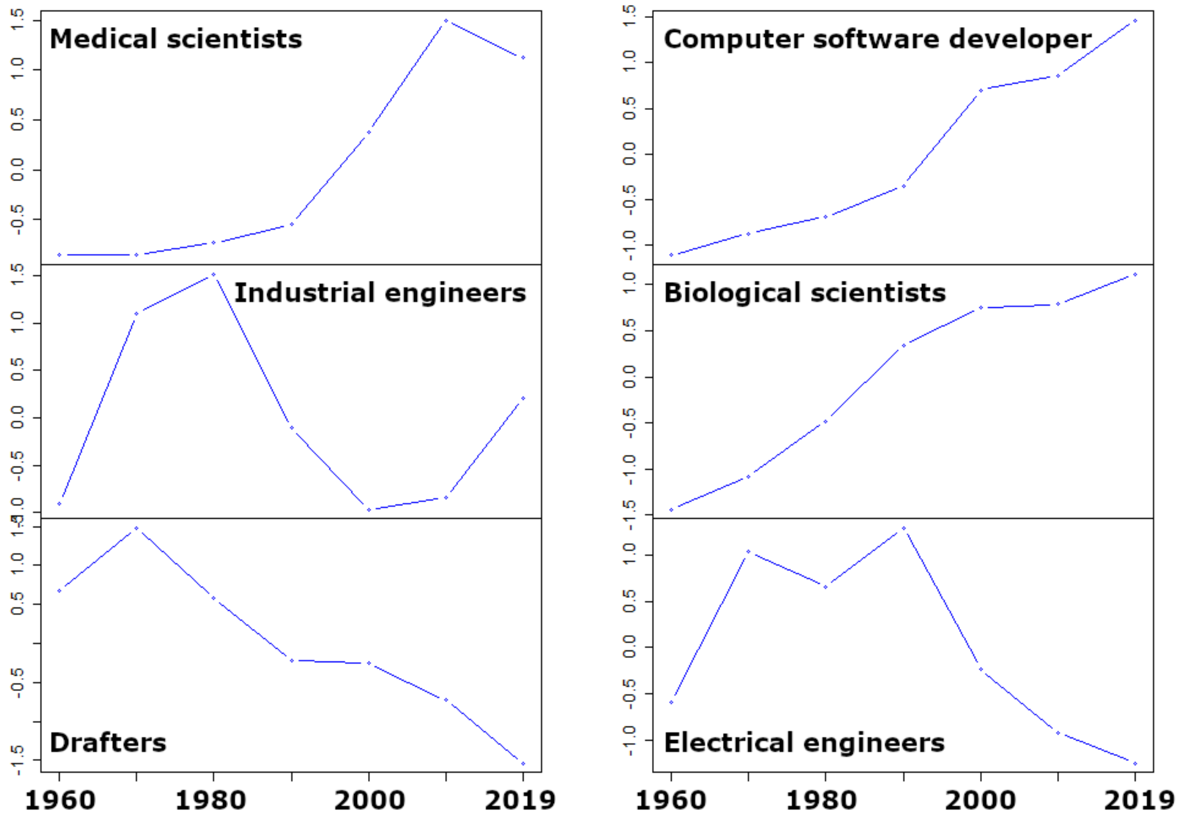

Figure 2. Time-series trajectories for selected occupations, 1960-2019
Notes: Graphs showing relative size trajectories of six occupations across the third industrial revolution. The x-axis (Time) is a decadal measuring beginning in Time 1 (1960) and ending in Time 7 (2019). The y-axis shows an occupation-specific z-score the occupations share of the labor force in each time period. Occupations that grew in their relative contribution to the overall labor force have higher z-scores in later years.

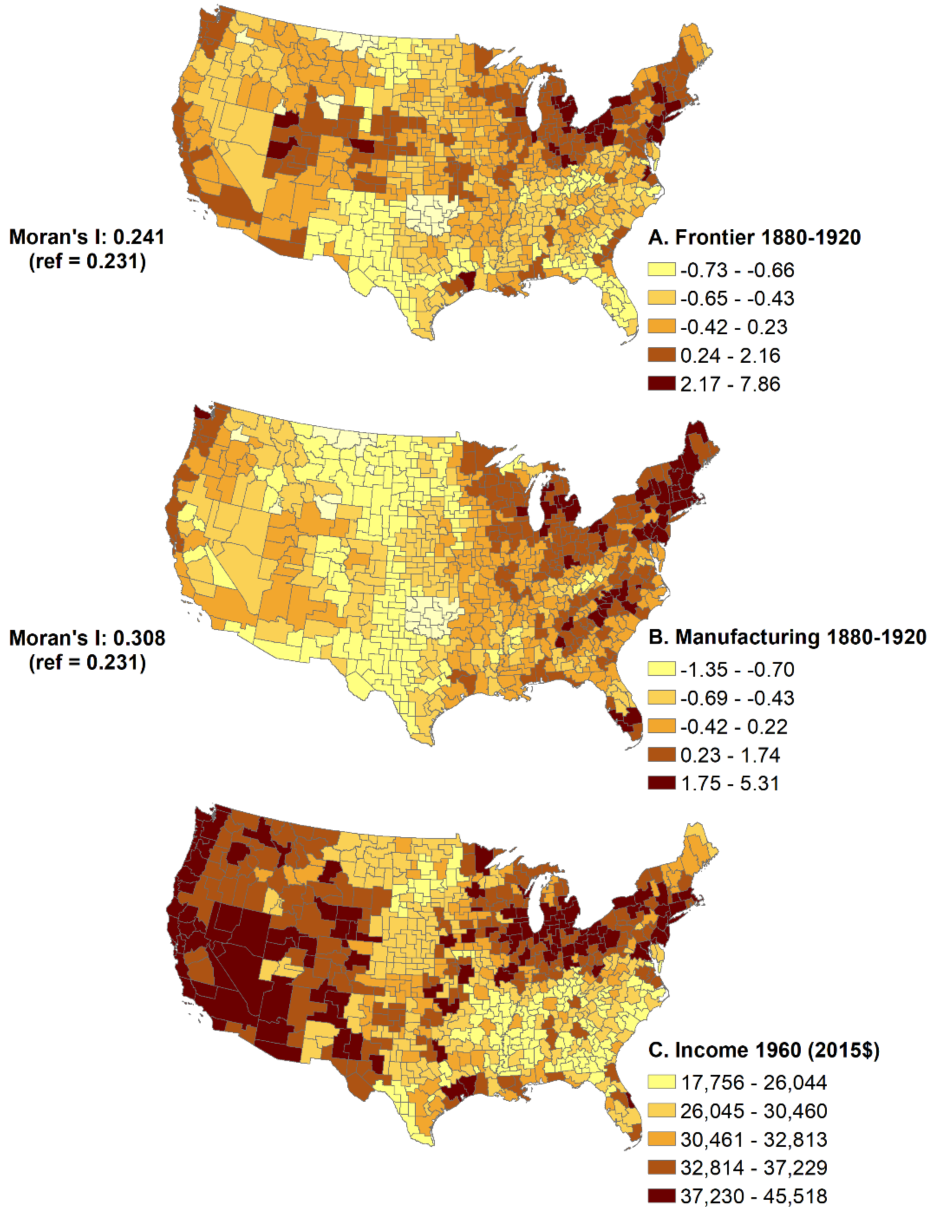

Figure 3. Distribution of workers and incomes in the Second Industrial Revolution

Notes: Maps showing the concentration of frontier manufacturing workers (A), all manufacturing workers (B), and income levels in 1960 across all commuting zones (C). Panel A shows the share of each commuting zone's labor force that are engaged as frontier manufacturing workers, standardized into z-scores. This is our seedbed measure for the third industrial revolution. Panel B shows the local the share of each commuting zone's labor force that are engaged in all manufacturing activities, standardized into z-scores. Panel C shows the average income levels of commuting zones in 1960. Income levels are adjusted to 2015 dollars. The break values for the bins are assigned automatically using geometric intervals. Moran's I statistics are calculated based on the distribution of worker counts using corner contiguity. We calculate Moran's I for counts rather than share so that we can benchmark our statistics against the whole working population ("ref").

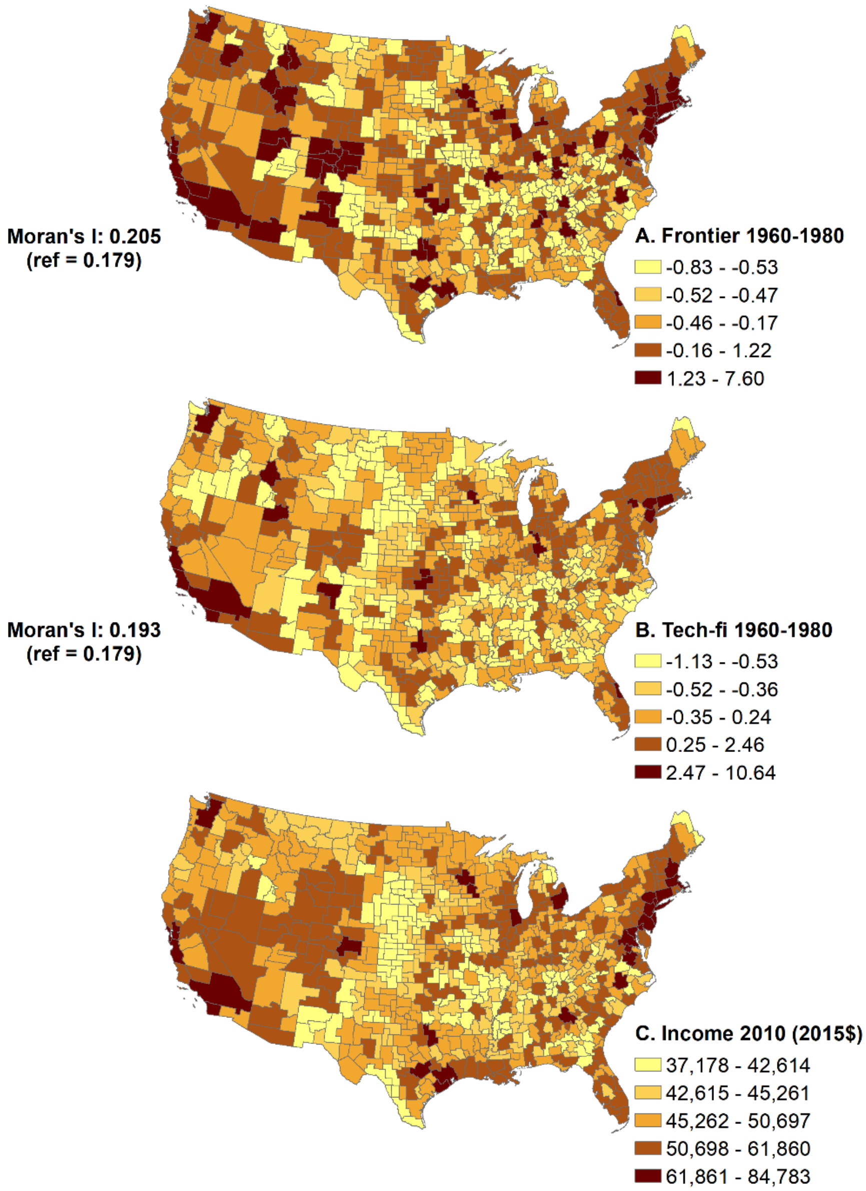

Figure 4. Distribution of workers and incomes in the Third Industrial Revolution

Notes: Maps showing the concentration of frontier technology and finance workers (A), all technology and finance workers (B), and income levels in 2010 across all commuting zones (C). Panel A shows the share of each commuting zone's labor force that are engaged as frontier technology and finance workers, standardized into z-scores. This is our seedbed measure for the third industrial revolution. Panel B shows the local the share of each commuting zone's labor force that are engaged in all technology and finance activities, standardized into z-scores. Panel C shows the average income levels of commuting zones in 2010. Income levels are adjusted to 2015 dollars. The break values for the bins are assigned automatically using geometric intervals. Moran's I statistics are calculated based on the distribution of worker counts using corner contiguity. We calculate Moran's I for counts rather than share so that we can benchmark our statistics against the whole working population ("ref").

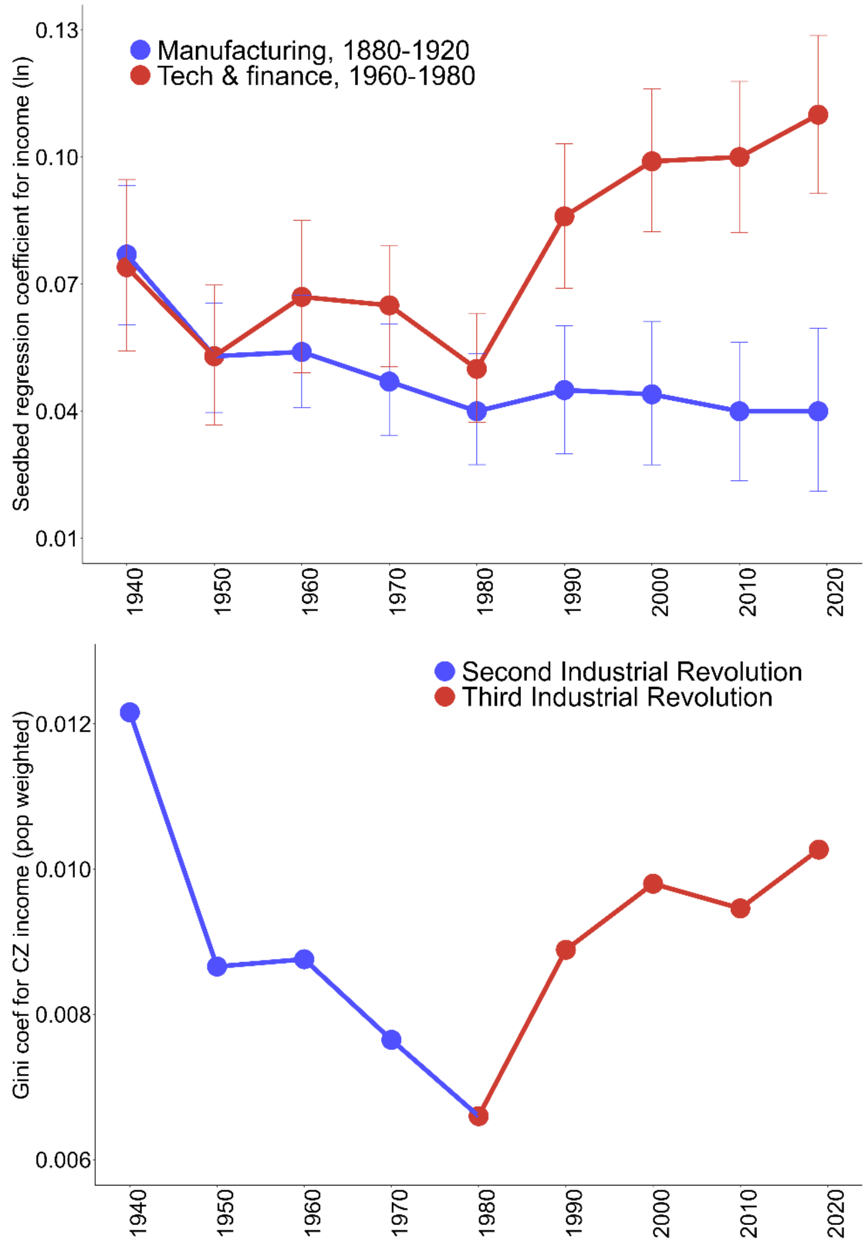

Figure 5. Spatial income inequality and seedbed persistence, 1940-2019

Notes: A graph showing the long-term persistence of historical seedbeds on income (Panel A) and general inequality in the distribution of income (Panel B) across approximately 700 consistent commuting zones areas from 1940 to 2018. The coefficients in Panel A were generated by regressing commuting zone income levels on the two historical seedbed measures, where the independent and dependent variables have all been converted into standard units. The first seedbed measure is based on frontier manufacturing employment shares from the 1880-1920 period and the second seedbed measure is based on employment shares in technology and finance from the 1960-1980 period. Confidence intervals are at the 95% level. The income inequality measure is based on a population weighted gini coefficient for CZ income levels in each period. Standard errors clustered at the commuting zone level.

Frontier occupations		Frontier industries	
Code	Description	Code	Description
35	Draftsmen	358	Miscellaneous machinery
7	Chemists	367	Electrical machinery, equipment
46	Engineers, mechanical	469	Miscellaneous chemicals
280	Purchasing agents and buyers	336	Blast furnaces, steel works
44	Engineers, electrical	376	Motor vehicles
95	Technicians, testing	476	Petroleum refining
33	Designers	337	Other primary iron and steel industries
42	Engineers, chemical	377	Aircraft and parts
45	Engineers, industrial	448	Apparel and accessories
49	Engineers (n.e.c.)	407	Dairy products
96	Technicians (n.e.c.)	499	Not specified manufacturing
41	Engineers, aeronautical	346	Fabricated steel products
47	Engineers, metallurgical, metallurgists	378	Ship and boat building
		456	Pulp, paper, and paperboard
		406	Meat products

Table 1: Frontier workers' occupations and industries, 1880-1980

Notes: Codes based on IPUMS 'occ1950' and 'ind1950'. Frontier industries listed here are a selection of the 20 largest industries by employment. This table is limited to the 15 largest industries.

Frontier occupations		Frontier industries	
Code	Description	Code	Description
229	Computer software developers	732	Computer and data processing services
64	Computer systems analysts and scientists	882	Engineering, architectural, and surveying
59	Engineers	891	Research, development, and testing services
53	Civil engineers	441	Telephone communications
214	Engineering technicians	322	Computers and related equipment
43	Architects	181	Drugs
76	Physical scientists	352	Aircraft and parts
73	Chemists	341	Radio, TV, and communication equipment
184	Technical writers	371	Scientific and controlling instruments
83	Medical scientists	362	Guided missiles, space vehicles, and parts
78	Biological scientists	321	Office and accounting machines
75	Geologists		
48	Chemical engineers		
68	Mathematicians and math scientists		
45	Metallurgical and materials engineers		

Table 2: Frontier workers' occupations and industries, 1960-2019

Notes: Codes based on IPUMS 'occ1990' and 'ind1990', themselves based on Census classification schemes. This table is limited to the 15 largest occupations.

	Second industrial revolution (1940-1980)		Third industrial revolution (1980-2018)	
	All workers	Frontier only	All workers	Frontier only
Share of labor force	-	1.8%	-	1.07%
Share college graduate	14.19%	40.00%	31.19%	74.72%
Average annual wage (2015$)	$42,982	$65,857	$56,174	$90,140
Northeast	30.57%	38.24%	19.37%	21.22%
Midwest	26.86%	38.96%	23.52%	17.30%
South	31.10%	13.85%	36.24%	32.54%
West	11.47%	8.95%	20.87%	28.95%
Lives in top 20 largest CZ	38.39%	46.40%	38.12%	51.71%
Frontier worker per 1000, 1960-1980	0.73	0.89	4.0	5.5
Obs	63,444,527	458,556	27,748,625	280,636

Table 3: Descriptive statistics for frontier workers across two industrial revolutions

Notes: Second Industrial Revolution period covers 1900 to 1980; Third Industrial Revolution period covers 1970 to 2019. CZ Frontierness is defined as in the equation in section 3.4. 'Largest' CZ defined in terms of total population.

Second industrial revolution				Third industrial revolution			
Region	Frontier per 1000, 1880-1920	Inc rank 1940	Inc rank 1960	Region	Frontier per 1000, 1960-1980	Inc rank 1980	Inc rank 2010
Youngstown	2.14	43	41	San Jose	13.1	5	3
Albany	1.89	49	80	Seattle	8.92	10	14
Detroit	1.80	2	1	Washington DC	8.55	2	1
Newark	1.70	4	7	Newark	7.37	9	4
Philadelphia	1.61	45	54	Boston	7.36	91	7
Milwaukee	1.52	17	13	San Diego	7.33	85	20
Pittsburgh	1.44	20	32	Denver	7.28	23	16
Cincinnati	1.44	35	27	Minneapolis	6.92	16	15
Cleveland	1.43	13	6	San Francisco	6.51	4	2
Toledo	1.33	25	17	Los Angeles	6.32	18	27
Buffalo	1.26	42	23	Dallas	5.68	47	23
New York	1.16	3	24	Bridgeport	5.59	20	5
Bridgeport	1.15	38	16	Fort Worth	5.58	87	56
Erie	1.14	88	133	Houston	5.43	6	24
Providence	0.97	92	256	Phoenix	5.43	95	58
Syracuse	0.96	93	62	Philadelphia	5.22	50	12
Chicago	0.95	12	4	St. Louis	5.14	48	41
Boston	0.93	24	69	Atlanta	4.90	78	22
Grand Rapids	0.91	64	51	Columbus	4.83	94	46
St. Louis	0.87	52	43	Indianapolis	4.82	68	51
Indianapolis	0.87	51	33	Chicago	4.58	7	13
Harrisburg	0.80	182	185	Pittsburgh	4.46	27	60
San Francisco	0.79	1	5	Cincinnati	4.45	44	42
Dayton	0.76	91	28	New York	4.44	24	8
Baltimore	0.76	76	106	Providence	4.29	192	43
Columbus	0.70	53	57	Baltimore	4.28	57	9
Portland	0.65	21	30	Syracuse	4.25	174	97
Reading	0.62	225	258	Kansas City	4.22	52	40
Seattle	0.61	5	11	Portland	3.99	36	33
Minneapolis	0.51	22	14	Cleveland	3.38	17	65
Los Angeles	0.50	16	3	Detroit	3.35	1	29
Birmingham	0.48	206	196	Dayton	3.27	73	190
Kansas City	0.45	75	58	Tampa	3.12	344	84
Houston	0.43	84	66	Milwaukee	2.88	28	49
Washington DC	0.40	14	10	Miami	2.80	135	98
Louisville	0.34	148	124	Sacramento	2.77	61	34
New Orleans	0.31	236	201	Buffalo	2.67	65	71
Atlanta	0.31	257	190	San Antonio	2.52	360	148
Scranton	0.23	159	372	New Orleans	2.44	83	77
Dallas	0.21	150	100	Louisville	1.20	134	100

Table 4. Income position of the 40 largest regions over two industrial revolutions

Notes: This table ranks the largest commuting zones in the second and third industrial revolutions according to their total rate of frontier workers per thousand workers. The commuting zones are labelled based on their largest incorporated or census designated place and ordered according to their seedbed measure.

	2nd Industrial Revolution (1940-1980)			3rd Industrial Revolution (1990-2019)		
	Income (ln)	Manufacturing Share	Frontier Share	Income (ln)	Tech-finance share	Frontier share
	(1)	(2)	(3)	(4)	(5)	(6)
Frontier manufacturing, 1880-1920	0.034***	2.877***	0.323***			
	(0.005)	(0.556)	(0.066)			
Manufacturing, 1880-1920	-0.008	4.026***	0.316***			
	(0.006)	(0.730)	(0.101)			
Frontier tech-finance, 1960-1980				0.027***	0.879***	0.505***
				(0.002)	(0.302)	(0.114)
Tech-finance, 1960-1980				0.005	0.728***	-0.0734***
				(0.009)	(0.159)	(0.036)
N	3,411	3,411	3,411	2,888	2,888	2,888
R2	0.950	0.701	0.666	0.891	0.816	0.827
Time variant controls	Yes	Yes	Yes	Yes	Yes	Yes
Time invariant controls	Yes	Yes	Yes	Yes	Yes	Yes

*p < 0.10, **p < 0.05, ***p < 0.01, CZ-level clustered standard errors in parentheses

Table 5: Estimates the impact of seedbeds on later outcomes.

Notes: Estimates from six regression models assessing the relationship between commuting zone (CZ) early frontier worker shares with income levels and worker employment shares. Models 1-3 cover the period from 1940 to 1980 and Models 4-6 span the years from 1990 to 2019. All models are based on commuting zone observations and include time-varying controls for population size, education level, as well as time-invariant controls for education and population levels in the seedbed period, and fixed effects for US census regions and decade. All income levels are adjusted to a 2015 basis. The high r-squared values in our models result from the strong geographic controls within our models, including the census region fixed effects. These estimates are weighted by population in the relevant seedbed period.