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Organizational Frictions and Increasing Returns to Automation: Lessons from AT&T in the Twentieth Century
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ABSTRACT

AT&T was the largest U.S. firm for most of the 20th century. Telephone operators once comprised over 50% of its workforce, but in the late 1910s it initiated a decades-long process of automating telephone operation with mechanical call switching—a technology first invented in the 1880s. We study what drove AT&T to do so, and why it took one firm nearly a century to automate this one basic function. Interdependencies between operators and nearly every other part of the business were obstacles: the manual switchboard was the fulcrum of a complex system which had developed around it, and automation only began after the firm and automatic technology were adapted to work together. Even then, automatic switching was only profitable for AT&T in larger markets—hence diffusion expanded as costs declined and service areas grew. We show that automation supported AT&T's continued growth, generating a positive feedback loop between scale and automation that reinforced AT&T's high market share in local markets.

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At the stroke of midnight on June 4, 1978, the Pacific Bell Telephone Co. initiated dial telephone service on California's Santa Catalina Island, replacing local telephone operators and completing AT&T's mechanization of the U.S. telephone network. The event took place nearly 60 years after the Chesapeake & Potomac Telephone Co. installed AT&T's first dial telephones in Norfolk, Virginia (November 1919)—when AT&T was on the cusp of becoming the country's largest employer—and 90 years after mechanical switching was invented (March 1889).

Automation technology today—from industrial robots to artificial intelligence—is an area of significant investment, research attention, and public interest (e.g., Acemoglu and Restrepo 2019, Muro et al. 2019). A recurring concern is that automation is about to dramatically displace human labor, with large consequences for workers and organizations (Autor 2015). Understanding what drives firms to automate activities, what obstacles they face, and how automation affects firm performance is important to understanding how these changes may unfold. The historical U.S. telephone industry would seem to be a setting for automation to nearly-frictionlessly diffuse: to a first order, it was one firm, selling one product, across local markets. Why, then, did it take AT&T *90 years* to fully adopt mechanical switching throughout its business—and what can its story teach us about the challenges of automation and its impacts on firms today?

To answer these questions, it is useful to begin by describing AT&T and its economic and technological context. From the 1880s to the 1980s, AT&T was the corporate parent of over two dozen operating companies and thousands of telephone exchanges across the country, which collectively comprised the Bell Telephone System. It was also the dominant U.S. telephone service provider until its court-led breakup in 1984. When AT&T's business developed in the late 19th century, it did so around a technology that required telephone operators to physically connect callers, involving ancillary inputs and linking to a number of other firm activities, from equipment installation and maintenance to billing. The complexity and labor demands of manual operation increased rapidly in large markets with billions of possible connections, and by the early 1920s, AT&T was the largest U.S. employer, with telephone operators comprising over half its workforce. Paradoxically, however, this scale was also AT&T's main source of competitive advantage, which was rooted in its ability to make the most connections of any telephone service provider.

Against this backdrop, we combine narrative and empirical primary evidence to explain AT&T's automation of telephone operation and its implications for the firm itself. Our core findings consist of three results. First, because AT&T's business was organized around operators, its automation was hindered by a tight web of interdependencies across its activity system. Making 'the switch' profitable required that the system and technology be designed to work together, and necessitated organizational learning, adaptation, and innovation in each. Second, exchange-level adoption of mechanical switching was driven primarily by complexity and economies of scale in local markets, and possibly also by union pressures. Finally, automation appears to have supported the expansion of AT&T's local residential service, which, while not on a differential growth trend pre-automation, grew quickly in local markets with mechanical switching. Automation was thus propelled by scale and contributed to scale, reinforcing AT&T's local and national dominance, which stemmed from its ability to make the largest number of telephone connections.

Despite significant interest and research on automation, much of this work overlooks how difficult it can be to integrate labor-saving technology in labor-intensive settings. Mechanical switching is an example of what we term 'integral' technology: one which must be integrated with many firm activities to create value.[1] The manual operators which it replaced were responsible for connecting callers, providing multiple types of service (e.g., local, long-distance, pay, information, emergency), tracking billing minutes, and more. On a day-to-day basis they also built rapport with customers, becoming a symbol of high quality service. The physical and organizational technology that made this system run—such as telephone sets, switching equipment, numbering plans, and directories—were all designed for manual operation. Prices, which were in most jurisdictions regulated, were also determined on the basis of (manual) operating costs.

To make the leap to mechanical operation, AT&T implemented a large number of changes to its business. These included new types of equipment and manufacturing, adding manual-mechanical interoperability; changes at individual telephone exchanges such as managerial training, operator downsizing, adding an installation and maintenance workforce for the mechanical equipment, shifting residual unmechanizable operator tasks across job titles, and physically redesigning telephone exchanges; changes in customer technology and behavior such as rotary dial telephones, new numbering systems, and a new onus on the customer to place calls unassisted; new approaches to cost accounting, with accompanying regulatory accommodation; and more.

These patterns are consistent with the literature on complementarity and strategic fit (e.g., Brynjolfsson and Milgrom 2013), which has shown that practices or structures that work well in one setting may not in others, because they create value through complementarities. A corollary is that technology transitions may require significant complementary investments to be productive (e.g., Gross 2018), including in intangibles (Brynjolfsson et al. 2021b), up to reconfiguring the firm itself. The depth of this problem, and the experimentation required to develop templates for adoption (Lawrence 2020), may in turn explain why technology transitions in firms take time to gain momentum (as in Bresnahan and Trajtenberg 1995). We argue that our new label is warranted because AT&T's adoption of mechanical switching is representative of a more general phenomenon that is common to automation when labor is at the center of a production system, but it does not fit existing conceptual categories like architectural innovation (Henderson and Clark 1990) or

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[1] We thank our colleague Wes Cohen for suggesting a label for this phenomenon.

general-purpose technology (Bresnahan and Trajtenberg 1995).

The challenge of integrating new technology into complex production environments may explain why it took time for the technology to first be deployed. But once it was refined, and a template for the necessary organizational and technical changes was in place, why did it take 60 years to diffuse across AT&T's system? The Great Depression and World War II caused slowdowns, but macro events alone cannot explain this lag. We argue that the economics of the problem do. Automation, like other capital investments, tends to diffuse first to large units with the scale to spread fixed costs, profiting on lower variable production costs. In this case, however, AT&T's goal was not shifting variable costs down, but rather limiting the rate at which the marginal cost of each subscriber grows, by reducing the complexity of serving large markets. As such, the benefits of the technology decayed quickly in smaller markets. Because much of the population lived in rural areas served by small telephone exchanges, long lags may have been inevitable.

Through this historical episode at one of the largest and most storied U.S. companies, we provide a lens into why non-manufacturing firms automate production and under what conditions it is likely to succeed. The key strategic insight is the importance of supermodularity and system-technology fit (Milgrom and Roberts 1990). Although our setting is historical, we argue this insight generalizes to other firms, industries, or periods (e.g., settings where similar automation has been installed, attempted, anticipated, or ruled out include consumer banking (Bessen 2015), maritime shipping, air traffic control, and postal mail sorting, among many others). Moreover, as Zolas et al. (2020) point out, if automation is both driven by scale economies and propels firm growth, it can create winner-take-all industrial dynamics that give rise to 'superstar' firms (e.g., Lashkari et al. 2019, Autor et al. 2020). Though AT&T was already the leading U.S. telephone service provider at the dawn of the dial era with 63% national market share, by the early 1930s this had risen to 79%, and most AT&T service areas were no longer competed. AT&T's most valuable asset was the size of its local and long-distance network, and automation tended to reinforce this advantage against existing and potential competition (similar to Seamans 2012).[2]

We believe the paper is distinctive in several ways. One is the size of the firm and its automation. Another is the specificity of the technology and the jobs replaced: in most settings, it is difficult to directly measure automation or its effects, and researchers must proxy with capital investment or factor shares, which make it challenging to know what machinery was purchased, how it was used, what jobs were displaced, and how the technology affected firm performance. With few examples

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[2] Automation was thus correlated with market power, especially in fast-growing markets (e.g., Bennett 2020). That is not to say that automation caused concentration per se—this also reflected AT&T's ambition to be the universal service provider in the 20th century, and a growing acceptance that the efficient industry structure was monopoly (61 Cong. Rec. 1988, 1921)—but it may have accelerated the trend, especially as independents struggled against AT&T's dominance and ceded markets through exchange swaps or acquisition.

where technology directly, and nearly completely, replaces an entire major category of work, this literature often is not able to fully probe what causes (or hinders) firms from automating specific jobs away, nor evaluate how doing so affects firms, industries, or product markets. The historical telephone industry is a setting where the technology maps directly to a specific job, adoption is measured precisely, and the industry was concentrated in a single corporation with extensive data and records of its activities, outcomes, and strategic rationale.

Though the setting is compelling, it is also distinctive in its concentration and regulation, raising questions on whether these features sped or slowed automation. For example, market power might depress incentives for innovation (Arrow 1962).[3] On the other hand, vertical and horizontal concentration (AT&T owned not only the regional operating companies and the long-distance telephone network, but also an equipment manufacturer, Western Electric) reduces other frictions to technology adoption. This high concentration may also be useful to thinking about how the results extend to modern settings, including modern technology companies (e.g., Amazon or the modern AT&T), where a small number of firms have significant market power. Regulation and non-market strategy might in principle have also factored into AT&T's adoption of mechanical switching—though as we will show, the evidence and the economics of the problem suggest otherwise. We return to these questions with more perspective near the end of the paper.

We proceed as follows. Section 1 provides a conceptual foundation for our analysis. Section 2 reviews the history of the U.S. telephone industry, features of the AT&T system, and the development of mechanical switching. Section 3 discusses organizational and economic drivers and obstacles to automation. Section 4 introduces our data and presents corroborating empirical evidence. In Section 5, we describe how mechanical switching, driven by economies of scale, impacted subscriber growth. In Section 6 we suggest an explanation for the long lags in diffusion. Section 7 wraps with additional discussion and poses questions for future study.

1 Strategic Context for Automation

To realize technological improvements, useful inventions must be recognized, refined, and applied in productive activities. A long history of research on technology adoption dating to Griliches (1957) and Rogers (1962) has shown that getting new technology into practice is not always straightforward and sometimes takes place over long horizons. High fixed costs and scale economies are often first order obstacles to widespread adoption (e.g., David 1966). Information, uncertainty, and hesitancy are also among the myriad challenges to diffusion (e.g., Rogers 1962). Technologies often also have to be adapted to specific applications—or applications to technologies (e.g., Gross 2018). A wide

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[3] The literature on this question, however, is conflicted, with mixed theory and evidence, and results vary for inputs, outputs, and adoption of innovation. See Cohen (2010) for a review.

range of organizations and activities have developed over time to address these challenges, from information interventions, to early-adopter subsidies to stimulate spillovers, up to entire cottage industries that support custom use cases and installations.

In principle, AT&T would seem to be about as well-positioned as any firm to adopt new technology. As we discuss in the next section, by the turn of the century it had scale in the national market and increasingly in local markets. It owned a constellation of operating companies which it could manage from the corporate center. It was vertically integrated and manufactured its own equipment, which allowed it to tailor technology to its needs and eliminated any risk of contractual holdups in supply. Why, then, did it take AT&T nearly 100 years to mechanize?

The argument we will make in this paper is that organizational barriers and the unit economics of individual local markets are the key to explaining these extraordinarily long lags. The intellectual foundation of our thesis is in the literature on organizational complements to new technology, and related work on which it builds (e.g., Teece 1986, Siggelkow 2001, Siggelkow and Levinthal 2003, Ethiraj and Levinthal 2004, Taylor and Helfat 2009). This work adds to historical observations by social scientists that new technologies sometimes come in bundles (Rogers 1962), and more recent research on the importance of complementarities and strategic fit in complex organizations, an idea formalized by Milgrom and Roberts (1990, 1995) which is now a widely-accepted insight among management scholars (e.g., Rivkin and Siggelkow 2003, 2007).

One setting where these themes have received significant research attention is in the diffusion of information technology (IT) over the last 40 years. Since Solow (1987) noted that "the computer age [is] everywhere but in the productivity statistics," a body of scholarship has emerged to explain this seeming paradox. Much of the explanation has centered around complementarities. Bresnahan and Trajtenberg (1995), for example, argued that general purpose technologies (GPTs) create value via complementarities, and as a result may be slow to diffuse until complementary technologies develop—although contemporary and subsequent work has debated whether the obstacles to diffusion are organizational or technological (David 1990, Bresnahan and Greenstein 1996, Goldfarb 2005).[4] Through the AT&T example, we contend they are part and parcel of the same problem: making organizations and technology congruent with each other.

An important strand of this literature has focused on intersections of IT and organizational design. Indeed, the use of IT in modern manufacturing was one of the motivations for Milgrom and Roberts (1990). Bresnahan et al. (2002) show that IT interacts with organizational design to affect performance: "Firms do not simply plug in computers or telecommunications equipment

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[4] Interestingly, the authors claim *semiconductors* to be a GPT, not computers or IT. More generally, although widely used as a metaphor, the framework is also limited by an inability to rule specific technologies in or out as GPTs, limiting its practical utility: as Field (2008) has pointed out, dozens of technologies have been labeled GPTs. The confusion may owe to the fact that generality is continuous by nature, not discrete.

and achieve service quality or efficiency gains. Instead they go through a process of organizational redesign and make substantial changes to their product and service mix." More recently, Brynjolfsson et al. (2021b) have argued that the necessity of complementary investment in intangibles like new business processes, managerial experience, and worker training can delay the measured productivity impacts of GPT-like technologies but lead to a take-off in later years, yielding a productivity "J-curve". Brynjolfsson et al. (2021a) similarly show that the impact of data analytics on performance is contingent on the presence of complementary assets and business practices like production strategy, high IT investment, and an educated workforce. Agrawal et al. (2021) argue that artificial intelligence will, in many cases, require "system-wide change", particularly in non-modular environments. These are but a few examples of papers making the case for complementarities as mediators of the effects technology on firm performance.

Implications for automation

This paper conceptually merges these streams in the context of automation, while introducing what we argue are important new considerations. Here it is useful to be clear on definitions: the Oxford English Dictionary (OED) defines automation as "the action or process of introducing automatic equipment or devices into a manufacturing or other process or facility." Automation is both more general and more specific than the preceding literature. It involves a broader category of technology than, for example, IT or computers (e.g., mechanical automation preceded the information age, with our paper as but one example). Yet it is also a specific application of some of the aforementioned technologies (for example, automation is but one use for IT). The fundamental departure, and an important conceptual building block, is that automation is a *phenomenon* to which technology is merely an input—as the OED definition above makes clear.

In some settings, automation reduces to a simple technology adoption problem—for example, household washers and dryers replacing laundering, or autonomous store-cleaning robots which can now be found in grocery stores. But we argue that in many cases, automation must be woven into a wider range of activities a firm undertakes, especially when labor was previously central to the firm, and doing so may require a fundamental reorganization of the firm's activities. A historical, extraordinarily detailed comparison of hand and machine manufacturing methods, published by the U.S. Bureau of Labor Statistics in 1899 (DOL 1899), illustrates this well. Holding the product fixed, machine production methods on average involved nearly four times the number of workers and twice the number of tasks as hand methods, but were completed in one-sixth the time (Atack et al. 2016). These productivity improvements coupled with changes in the division of labor imply significant changes in organization under machine methods.

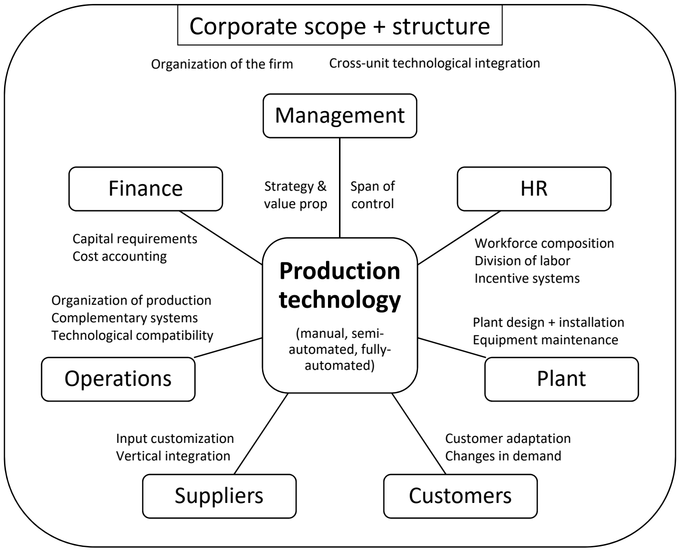
Recognizing this difference, we can point out a distinction between two types of problems: one where technology, often standardized, is simple to deploy with few other changes, and others where technology is tightly interwoven into a web of firm activities, and changes in technology may require more adjustments. For example, consider the early use of charge cards by retailers: this required little more than taking a customer's information and sending it to the card issuer (which screened applications, collected and remitted payments, and managed accounts). Contrast that to barcodes, which first diffused into the retail sector in the 1970s (Basker and Simcoe 2021). Barcode scanning substituted for many basic tasks of cashiers, like price tagging or ringing up sales. For retail stores to adopt barcode scanning, they need not only scanners, but also IT systems. They also need suppliers to package products with clearly-printed labels. The cashier's role changes. So does the customer's. It is this latter category of technologies that challenges the way information is processed and work is done. In the case of barcodes it affected the organization of the industry (e.g., the rise of "big box" stores), the composition of its workforce, the nature of the store clerk's job, store operations, and interactions with customers and suppliers (Holmes 2001).

In these cases, technology is *integral* to production, in many senses of the word: constituent to a larger system, deeply embedded, and essential to its functioning. In the cases we have in mind, it is part of an organization's sinew. This notion is distinct from others in the literature. It comes close to Henderson and Clark (1990)'s conception of "architectural innovation", but is nevertheless distinct: integral technology may require investments in complementary inputs but not the systemic upheaval that Henderson and Clark's architectural innovation implies (the authors themselves write that "the replacement of analog with digital telephones," a similar transition, was not architectural). Its closest cousin might in fact be GPTs—but many GPT applications are not integral, and perhaps more importantly, integral technology need not be a GPT. We will argue that the technologies studied in this paper—manual and mechanical call switching—were 'integral' to telephone service in this sense, but they would not meet these other definitions.

Specifically, what we seek to convey with this new label is that production technology can interact with nearly every feature of the firm, including its management structures and hierarchies, organizational form, corporate scope, teaming and division of labor, workforce composition, incentive mechanisms, operations systems (including information systems), finance and accounting, building and plant, customer and supplier relationships, and even product offerings—as we illustrate in the inset below. Depending on the firm and setting, each of these organizational features may be tied to the firm's production technology, and converting from manual to labor production may thus require either a flexible technology or other organizational changes. The examples of labor-saving technology we have touched on thus far—ATMs, containerization, automatic postal sorting, barcode scanning—required changes in most of these activities.

What do these ideas bring to our understanding of automation? From our perspective, it provides

Potential interdependencies between technology and activity system



a framing that recognizes the complexity of fitting automation into strategy and can explain why automation often takes a long time to percolate through firms and across the economy. In contrast to the literature emphasizing the importance of complementary technology or business practices, it allows that *technology be adapted to the firm*, not just the firm to the technology. As we will show, AT&T's technology and activity system developed together.

The thesis of this paper, as is now clear, is that AT&T's automation of telephone call switching was impeded by the strategic challenge of replacing one integral technology with another: telephone operators with mechanical call switching. Through this case study we have an opportunity to learn how AT&T—one of the most storied and historically-important companies to U.S. economic development—approached this problem, and what its implications were for the firm, for the industry, and for our broader understanding of automation.

Increasing returns to scale

This paper also links to growing concentration and increasing returns to scale in the modern U.S. economy (for recent summaries see Shapiro 2019, Lamoreaux 2019, Philippon 2019). Some points of concern include increasing markups, declining dynamism, labor's declining share of income, and other consequences—which in the technology industry can extend to consumer privacy and proliferation of misinformation. Several papers attribute these trends to changes in industry structure or weak antitrust enforcement. Autor et al. (2020) and Van Reenen (2018) provide a more nuanced view, arguing that technology and trade are changing the returns to scale in many industries, leading to winner-take-most economies and superstar firms.

Scale will generically make firm investments in automation more attractive, shifting variable costs to fixed. A new insight, however, is that firm size may be especially important for realizing the full benefits of integral technologies: large firms can amortize not only the cost of the technology, but also the substantial fixed cost of learning how to incorporate it into the business. With thousands of telephone exchanges, AT&T could spread these costs across its system once this problem was resolved. Large firms might thus be especially advantaged in adopting technology which enhances productivity but requires changes in the organization of the firm—suggesting that it is one channel through which large firms may extend their market power.

These issues thus connect intimately to our study of AT&T, not least because AT&T was the 20th century archetype for monopoly. As a high-tech service provider in an industry with strong network effects, it also presaged many of the economic issues and debates today. The parallels are perhaps strongest with modern internet communication firms which control physical infrastructure analogous to the telephone network, like wired or wireless service providers (e.g., Comcast or Verizon). But they also extend to firms in other industries like Apple, Google, Facebook, and Amazon, whose economic power is rooted in scale and network effects. Amazon may be the modern posterchild for these issues vis-à-vis automation, which it is increasingly incorporating into fulfillment operations and which reinforces its competitive advantage.

2 Historical Background

The U.S. telephone industry was born in 1877 with the founding of the Bell Telephone Company, a year after Alexander Graham Bell's successful demonstration of the telephone. The next year, the first telephone exchange was opened in New Haven, CT, and within a few more years Bell had licensed exchanges in many major U.S. cities, begun building connections between them (under its AT&T subsidiary), and acquired a telephone manufacturing company (Western Electric). In 1899, AT&T became the parent of the Bell System, which was comprised of subsidiary regional operating companies which served exclusive territories around the country.

The expiration of the original Bell patents in 1894 sparked the entry of thousands of "independent" operating companies which built competing networks in large cities and entered markets (especially rural areas) where AT&T had not, and in 1907 AT&T's share of U.S. telephones was down to 51% (U.S. Census Bureau 1902). Thereafter, AT&T focused on consolidating all subscribers and markets into one system, aggressively acquiring independents and refusing interconnection to those outside its network. This attracted scrutiny from the Department of Justice (DOJ), and a settlement in 1913 effectively made AT&T a regulated monopoly, with interstate service regulated initially by the Interstate Commerce Commission (ICC) and later the Federal Communications Commission (FCC), and local service regulated by state utility commissions.

The functional units of each operating company were individual telephone exchanges, which connected to subscribers and were in turn connected to each other via trunk lines. Telephone exchanges performed many functions, from installation to billing, but their core function was connecting telephone calls: at each telephone exchange, human telephone operators physically connected calls by plugging wires into a switchboard—a task known as *call switching*. From its founding, AT&T's switching equipment was designed to be manually operated (though as we will discuss below, AT&T experimented with automatic equipment for most of its history, even before it began to adopt it). As its business developed from the one New Haven exchange with 50 subscribers (New Haven District Telephone Company 1878) to a sprawling cross-country network with millions of users, it did so on the presumption that operators would be connecting calls.

Structure of the telephone network

Appendix Figure A.1 shows the geographic scope of AT&T's business as of 1891, 1898, 1904, and 1909. Each node in these maps marks a local exchange or service area in the Bell system (serving nearby, local customers), and each edge marks a trunk connection between them. Given the cost of installing its physical infrastructure, the speed with which AT&T expanded is astonishing: in 1891, its scope was limited to the northeastern U.S.; by 1898, it was providing service across much of the country east of the Mississippi River, and by 1909 it had exchanges throughout the U.S., with its densest coverage across the eastern half of the country.

From New England Telephone & Telegraph to Pacific Bell, the regional operating companies owned and managed this network, providing service in their respective territories (Appendix Figure A.2). Though these firms were geographically exclusive and independently managed, they had the same parent, business model, technology, and organizational structure. This structure is well-summarized by the National Labor Relations Board, which in 1944 described the Southern Bell Telephone Co. as having a headquarters and eight geographic divisions, subdivided into districts, which together managed over 900 telephone exchanges across nine states (NLRB 1944).

Using this infrastructure, the Bell operating companies provided two main types of telephone service (local and long-distance) and supported three main categories of customers (business, residential, and payphone). Customers leased their line and their telephone sets from the telephone company. They were then typically charged per minute for calls, with specific rates varying in distance: local calls (within the same exchange) were often free, local toll calls (to other exchanges in the same service area) were charged a low rate, and long-distance toll calls (to other service areas) a higher rate. Telephone companies also offered other services, including information service (e.g., directory assistance) and emergency service (i.e., 911). They also supported private branch exchange (PBX) service, through which large organizations such as businesses, hotels, or apartment buildings could host an internal switchboard where an internal operator would route incoming, outgoing, and internal calls to/from "extensions" to individual telephone sets within the organization. In these cases, the telephone company typically leased out both the PBX switchboard and an operator to the subscriber. All equipment needed for telephone service in the Bell system, whether on the exchange side or customer side, was made by Western Electric.

The telephone business required a wide range of firm activities. These telephone companies needed to not only build general transmission infrastructure, but also wire the homes and offices of individual subscribers and install their telephones. This equipment had to be manufactured, acquired, and then regularly maintained, expanded, and upgraded with new technology to support new services and increased traffic. Telephone companies also needed plant and equipment for their local exchanges. They needed to set prices, monitor calls, bill customers, and collect payments, as well as manage a complex cost accounting problem that involved numerous layers of fixed costs. They needed managerial, human resources, and public relations processes, including for working with regulators. And above all else, they needed to connect calls.

Reflecting this expansive scope, and the scale of the industry, their labor needs were significant—albeit overwhelming concentrated in operators. For example, of the nearly 215,000 individuals in the 1920 census who reported working in the telephone industry, 50% were telephone operators; 28% were linemen, servicemen, and other laborers; 8% were bookkeepers, secretaries, and other clerical workers; and 3% were electricians and electrical engineers. As the network grew, so did its workforce: by 1930, there were over 140,000 telephone operators in the telephone industry, the vast majority of which were women (Feigenbaum and Gross 2021).

Functions of the "Central Office"

Though the operating companies performed core functions like price-setting, system planning, and engineering studies at the corporate level, the day-to-day work of administering telephone service took place at telephone exchanges (also called Central Offices, in the parlance of the Bell system), by the workers they employed. A typical exchange had four principle departments. The Traffic department was responsible for operating the switchboards—in other words, directing traffic. The Plant department installed and maintained telephone equipment at the exchange and in the area it served. The Commercial department took new orders and requests for service changes, prepared bills, and collected payments. The Accounting Department kept financial records. Each exchange also had its own management and business office (NLRB 1944).

The operating floor was the heart of an exchange and abounded with activity, as Appendix Figure A.3 conveys with photographs of operators at work. An operator's job, in essence, was to take and place call requests. Gross and Kerr (2018) describe this work as follows:

> Prior to the introduction of dial service, customers who wished to make a telephone call simply needed to lift their handset off of its hook, speak to an operator, request a number, and wait for the connection to be made. Removing the handset from its station completed a circuit over the wires to the central office, sending a signal to the operator that a user was on the line. The next available operator would then plug her headset in to the user's jack and inquire, "Number please?" The caller would then give the number, and the operator would locate the destination jack and connect the call ... or pass the call to another operator who would begin building a circuit.

Telephone exchanges housed several categories of switchboards and operators. As Erickson (1947) explains, an "A" board operator would watch her board for pilot lights indicating a pending caller and take customer orders. If the destination was local and she was working a "dual" switchboard, she would connect the call directly; in most cases, however, she would pass the call to a "B" board operator who would ring the destination and complete the connection. In some cases, the "A" operator might first need to work with a "tandem" board operator to secure a trunk line to the destination telephone exchange. Operating rooms also had "long-distance" operators, who specialized in building long-distance connections; "information" operators, who served in an auxiliary capacity and could help customers look up telephone numbers by name and address; and "intercept" operators to troubleshoot when callers gave bad numbers, calls were disconnected, or customers had line troubles. The "A" operator not only was responsible for taking incoming call requests, but also for monitoring calls, tracking call duration, and writing billing tickets. According to Erickson (1947), "A" operators might connect 200 to 300 calls per hour at peak times, and "B" operators 800 to 1,000 calls per hour. In an official company occupational classification, AT&T (1917) similarly lists example duties of telephone operators as including "Operate at 'A' position", "Operate at 'B' position', "Do tandem work", "Do toll work", "Do rate quoting work", "Do directory work", "Furnish information to subscribers", "Do trouble work" and more.

From these descriptions alone, it is clear that manual operation was by this time a complex activity requiring significant division of labor and coordination. Keeping this system in sync was its own challenge, especially at the pace that AT&T desired. In the early years of the telephone industry, or in small markets, fewer operators were needed and each could perform a wider range of tasks; at the extreme, some communities' call volume was too low to justify 24-hour or weekend service. In large markets, however, telephone exchanges were staffed around the clock and relied on specialized operators and switchboards to connect users at scale. This complexity not only necessitated more operators, but also better operators, who were in limited supply.

Development of automatic switching

The first mechanical switching system was invented by Almon Strowger, an undertaker in Kansas City in 1889.[5] Over time, this system evolved to be used with rotary dial telephone sets, where each turn of the dial transmitted an electrical pulse which actuated a sequence of selectors at the telephone exchange until a circuit was completed between the caller and the telephone dialed—without manual intervention. The Strowger patent (issued 1891) was commercialized via the Strowger Automatic Telephone Exchange Company, which became the Automatic Electric Company, a competitor of Western Electric which supplied independent (non-AT&T) telephone companies. The Strowger system was initially adopted by a handful of independents, especially for small exchanges in rural areas where it was difficult to provide 24-hour manual service.

AT&T also claims to have begun research and development (R&D) on automatic operation around this time, but early development was slow and unpromising. Research intensified around 1900, after one of the operating companies expressed interest. In the early 1900s, a 100-line automatic exchange was developed and purchased by a few dozen Bell exchanges, but these pilots were unsuccessful: "operating experience showed that the dial telephone art was not sufficiently advanced to justify the use of such equipment" (Freeman 1937). A 10,000-line system was developed in 1903, but it too "did not permit any material savings or better service than manual" (Freeman 1937). At this point, "The future of the automatic exchange with Bell Companies [was] more or less uncertain" (Freeman 1937, quoting AT&T's chief engineer in 1904).

Part of the challenge was that manual switching, by this time, was in an advanced state of development. For example, Freeman (1937) explains, "By 1905, the manual system had been developed to a point where it was giving fast, accurate, and dependable service in practically all sizes of exchange areas." Mechanical switching had not matched manual methods on cost and performance, and moreover, AT&T worried about "the practicability of putting a complicated system under the control of the subscriber without the supervision of a skilled operator."

Research into automatic switching at AT&T nevertheless continued: Freeman (1937) alleges that "from 1907 on, the automatic system was the subject of almost continuous laboratory test, field studies, and economic comparisons." However, it would be another decade until automatic switching could match or beat manual operation on connection times and error rates, and internal estimates suggested it may generate savings in large and medium cities. In 1917, AT&T began formally recommending that its operating companies adopt mechanical switching in large, multi-exchange cities, backing this recommendation with evaluations of its relative connection speeds, accuracy, cost, versatility, customer sentiment, and the severity of the "labor problem" (Gherardi 1917). The

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[5] Allegedly, Strowger's incoming telephone calls were being redirected by the local operator, who was also the wife of a competitor, and his inventive motivation was to disintermediate the operator.

engineering department anticipated that mechanization would reduce operating requirements by 70% to 80%. In Section 3, we will address why this mattered.

At first view, it might seem as if mechanical switching was primarily a technological problem. But AT&T documents also make clear that transitioning from the manual to mechanical system required a substantial mount of organizational learning. Much of this learning came through field trials of mechanical systems at individual exchanges, such as in Newark, NJ (1913) or Wilmington, DE (1917). But because independents were the earliest adopters of mechanical switching, AT&T also learned by observation, actively studying the use at other telephone companies.[6] It also learned by acquisition, alleging that "Experience was obtained with a number of independent plants of the step-by-step type which were acquired" (Freeman 1937). However, learning by doing was likely the most impactful, and continued into the dial era as AT&T refined its approach to cutovers, which enabled later exchanges to start further down the learning curve.

Table 1 summarizes the growth of the telephone industry from 1902 to 1932, using data from the quinquennial Census of Electrical Industries. Over the period, the industry grew nearly 20x in miles of wire, 10x in number of telephones, 6x in number of calls, and 5x in employment. By 1932, AT&T served nearly 80% of all telephones in the U.S. (even more in urban markets). Figure 1 shows the diffusion of dial within the Bell System, which increased rapidly—reaching 32% by 1930 and 60% by 1940—but ultimately extends into the 1970s.

[Figure 1 about here]

3 AT&T's Drivers and Barriers to Automation

AT&T archival records provide evidence on its reasons for automating call switching. As Freeman (1937) explains, in the late 1910s, the firm was confronting three pressures: "(a) a sharp rise ... in operators' wages; (b) the difficulty of securing and retaining an adequate number of operators ... [and] (c) the complexity involved in rendering manual service." At the 1916 Bell System Technical Conference, an AT&T engineer noted the limits to manual operation and emphasized the "necessity of proceeding with a machine switching program in order to insure that the service requirements of the future could be adequately cared for" (Freeman 1937).

AT&T's first problem was that manual switching had significant diseconomies of scale. Because the number of possible connections in a telephone network is quadratic in users, manual operation became especially complex in large markets. This challenged the ability of manual systems to make

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[6] For example, AT&T's internal history of the development of automatic switching recounts that "In 1904, extensive tests and observations were made in the [independent] Strowger installations at Fall River and New Bedford, Mass.; Chicago, Ill.; Dayton, Ohio; and Grand Rapids, Michigan (Freeman 1937).

timely and accurate connections, and necessitated more operators, a "better grade" of operator, and more and better training—as operators needed to reach more switchboard positions, learn more exchange names, and be able to connect calls through more trunking (Freeman 1937). As Lipartito (1994b) writes, "At large urban telephone exchanges, managers quickly perceived [manual] switching to be a potentially serious bottleneck." Rural areas, on the other hand, were "the easiest ones to handle from an operating standpoint" (Charlesworth 1923).

A second concern was a tightening labor market and rising wages, particularly for young women. Internal documents in places attribute this to labor market competition. For example, Orbach (1930) writes "During the past 20 years, particularly since the war, other employers of labor have been competing with us for this class of labor, with consequent upward jumps to our wage schedule and consequent need for higher [telephone] rates." Elsewhere it is attributed to World War I labor shortages or general price increases. In our analysis, we will not find strong evidence that trends in employment rates were related to local adoption of mechanical switching. But a distinct source of pressure we will explore was organized labor, with operator unions bargaining and striking for higher pay, shorter workdays, contiguous shifts, paid vacations, and more (IBEW 1921, 2016). Because operators were the fulcrum of the entire telephone network, strikes could cause near-total disruption to telephone service, and sometimes did (Lipartito 1994b).

The third concern was that the operating companies were facing a shortage of qualified operators (Gherardi 1917). The root of the problem was that AT&T's growing operating demands exceeded population growth (Orbach 1930). Although "this condition did not result in difficulty securing operators until the period 1910 to 1920," it was a predictable dynamic. The shortage of operators was also in part a problem of AT&T's own making, as it was committed to hiring operators that met very specific criteria: operators were generally young, white, American-born women, and were required to have "a pleasing voice, alertness, manual dexterity for handling equipment and tools of the job, legible penmanship, ability to make simple calculations rapidly and accurately, a sense of teamwork for cooperating with other operators in establishing connections, a stable disposition not easily ruffled by irritable customers, and courteousness" (Erickson 1946). The set of eligible workers was thus narrow. Orbach (1930) goes on to explain that "If our present rate of growth continued, in a few years we would need most of [this population]."

Organizational barriers

Given these challenges, why was telephone operation not automated sooner, or faster? Not all of these problems were new or unexpected: given that it only takes 45,000 subscribers for a service area to have >1 billion connections, the complexity of manual operation was already an issue in many large cities by 1910 and could be expected to become one in other service areas over time. Despite its limitations, however, AT&T was relatively bound to manual operation. From the dawn of the telephone era, telephone systems had been designed around the operator, who had only become more embedded in AT&T's activity system over time as it matured. Put differently, operators not only sat at the nexus of the physical network, connecting callers; they were a cornerstone of the entire business. Telephone sets, switching equipment, numbering plans, and directories were all designed for manually-operated telephone service. Operators were critical to assisting callers who did not know how to reach their destination or were having connection problems. They monitored call durations and wrote up tickets for billing. They were the principle source of variable costs in an otherwise fixed cost heavy business, whose pricing (and regulatory approval) was a function of the system's cost structure. Finally, operators built relationships with customers and provided a human touch to telephone service, which was the status quo ante against which dial service would be compared. Figure 3, Panel (A) shows an activity map of the different activities that telephone companies undertook and the connections between them, highlighting the ways in which telephone call switching was integrated with the rest of the business.

[Figure 3 about here]

The embeddedness of operators in the telephone network, and abundance of complementarities, meant that changes to key inputs—like switching technology—risked upending AT&T's entire production system unless the technology and this system could be designed to work together. AT&T also needed to prepare contingencies for when the technology failed, and convince operating company managers to adopt mechanical switching, overcoming their skepticism on its reliability and cost savings. Altogether, these obstacles were considerable.

How were these obstacles overcome? In short, through dozens of innovations, including changes in both switching technology and in AT&T's business. Lipartito (1994a) writes, "Strowger switches required a number of improvements before they could be used ... In addition, several other technical refinements were needed to integrate manual and machine switching methods and to link automatic local and manual long distance switching ... Assuming mechanical switches could compete with manual methods in speed and cost, there were ... system issues to consider."

In Figure 3, Panel (B) we list the many changes that mechanical switching required in operating companies' business, as well as among other industry participants. We group these into five categories: changes at the AT&T corporate parent, changes at the central office, changes in customer behavior, changes in customer technology, and regulatory accommodation.[7]

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[7] Changes at the AT&T corporate parent could be further subdivided into corporate activities and supplier activities, since AT&T in this context was both parent and supplier to the operating companies.

To a first order, many of these changes are easy to recognize. As we discussed in Section 2, AT&T invested decades, and significant capital, in improving automatic switching equipment to the point where it was competitive in cost and performance with manual switching. These investments were prerequisite to mechanization. In addition to creating and refining mechanical switching designs, AT&T also needed to develop technology that would allow this equipment to interconnect with an otherwise still-manual network, including making connections between manual and dial subscribers where both existed, and making automatic switching compatible with information, emergency, and long-distance services. Moreover, AT&T needed more than this technology alone: it also needed to produce fully-vetted recommendations and protocols for adoption, and educate operating company managers on the new technology. Through its Western Electric subsidiary, it also needed to develop capabilities to manufacture automatic equipment at scale.

The greater part of these adjustments took place at telephone exchanges. Each central office which mechanized call switching had to replace its equipment and re-wire the exchange. At times, this required constructing entire new buildings and physically re-locating operations. The automatic equipment required new approaches to information and emergency services, call monitoring, and caller assistance, which in the previous system would have been performed or facilitated by the "A" operator who took each call—a worker type which was automated. Exchanges needed to overhaul their workforce, slashing operators and hiring new workers to maintain the mechanical equipment. They also needed a transitional workforce in the months prior to automation, with operating jobs that would be eliminated when the new technology was in place.

Mechanical switching required new handsets, new telephone numbers, and the issuance of new telephone directories. One of the most important but subtle, non-obvious complementary innovations which made dial service feasible—without which it may not have been possible—was to AT&T's numbering system (Freeman 1937, Turner 1958). The problem AT&T faced was that telephone users in multi-exchange cities were identified by an exchange name plus a 4-digit number. Prior to dial, callers gave the operator the destination exchange *by name* and the subscriber number—a system which was not compatible with a numeric rotary dial. The now-ubiquitous breakthrough innovation was to map numbers on the dial to letters in the alphabet, so that users could specify the destination exchange by a 3-character prefix using the same ten numeric slots which they used to dial the other digits of the destination number (Turner 1958).

Dial service also required a number of changes in user behavior, the most obvious being that users had to be taught to dial their own calls. This user education took place through a mix of media campaigns—including through newspaper and radio announcements, and movie previews—and in-person demonstrations. Although now routine, telephone dialing was new for its time, and some users were upset at having to dial their own calls. The technology thus required user acceptance, or accommodations for those who refused it.[8] In some cases, users may have made organizational adjustments, including hiring secretaries to place and take calls.

Finally, mechanical service required fundamentally different cost accounting, shifting variable labor costs to fixed capital costs, which in turn shifted cash flows and rates of return. Prices, however, could only be changed with regulatory approval, which was thus its own obstacle. Relatedly, AT&T and its subsidiaries also faced significant public scrutiny over its elimination of operators, which was inflamed by a steady flow of newspaper articles describing the job losses accompanying each cutover, and which led to a sequence of government reports and eventually Congressional hearings pitting AT&T executives against operator union representatives.

As this discussion conveys, integrating mechanical switching into the conventional telephone company business system was a complicated endeavor. The number of ways in which this system needed to be adapted to automatic technology (or vice versa) is among the reasons why it took decades for AT&T to begin using it. Through a mix of deliberate testing and trial and error, AT&T and its subsidiaries eventually developed a template for adoption which could be deployed around the country, one exchange at a time. We see this reflected in newspaper articles describing its standard process: two to three years of planning and investment, distribution of dial handsets and directories, user training, transitional labor, and eventually, physically reconnecting wires from manual switchboards to mechanical equipment, often in a matter of minutes, after which subscribers would begin using their dial phones. Even then, as Figure 1 indicates, mechanical switching took time to diffuse across AT&T's network, for reasons we examine next.

4 The Sequence of Adoption

4.1 Data

The organizational barriers to AT&T's automation are largely qualitative, but the economic forces explaining its procession, and its impacts, are empirically testable. To evaluate these questions, we combine several sources of data, including city-level data on market size, telephone penetration, and labor market characteristics. At the core of this exercise, however, is a new hand-collected dataset of local cutovers to mechanical switching across the U.S. through 1940. Because the exchange-level adoption decisions were made by the operating companies, there is no one list of all Bell cutovers in AT&T records (Hochheiser 2017). We instead rely on a combination of historical newspaper reports and an AT&T administrative list of cutovers in large U.S. cities.

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[8] For example, when dial telephones were unexpectedly installed in U.S. Senators' offices in Washington DC in 1930, the Senate introduced and passed a resolution demanding that they be replaced with manual telephones (Minneapolis Star Tribune 1930). Similarly, when the New York Telephone Company replaced Wall Street's manual lines with dial service, J. P. Morgan "positively refused to use the dial system," and the company had to lay a special line to his office for manual service (Salt Lake Telegram 1924).

We exploit the fact that dial cutovers were nearly always locally-reported, due to the public's need to know when to begin using their dial phones and public interest in the new technology. We searched three online repositories of historical newspapers—Newspapers.com, NewspaperArchive.com, and GenealogyBank.com—for reports of cutovers between 1917 and 1940, and reviewed over 26,000 newspaper pages to determine (i) whether an article described a cutover, (ii) when it took place, and (iii) the cities affected. We supplement these data with administrative data from an AT&T list of the 164 U.S. cities with population >50,000 in 1937, which provides the date of each city's first Bell cutover (if any) and the fraction of Bell subscribers on dial by December 31, 1937, which we update to 1940 with additional manual research (AT&T 1937). Between the newspaper and AT&T data, we identify 688 U.S. cities with a cutover by April 1, 1940 (the enumeration date of the 1940 census, which we use as the end of our sampling window).[9] We also measure these cities' earliest cutover. As we document in Appendix B, the majority of these cities were sufficiently small that the entire population was cut over to dial in one discrete event.

We merge these data with city (i.e., local market) characteristics which we aggregate from IPUMS complete count U.S. census data for 1910 to 1940 (Ruggles et al. 2019), which provides microdata on the entire U.S. population enumerated in each census. We first undertake an effort to harmonize city names (Appendix B), and restrict our focus to cities which appear in all four years and have population >2,000 in 1920, which yields a panel of 3,027 cities. For each city and year, we then measure a number of characteristics, including the adult (16+) population, the demographic composition, and workforce characteristics, aggregating up based on measures of individuals' occupation and industry. We use these data both here (in studying the empirical drivers of automation) and in the appendix (where we present ancillary results).[10]

We use annual editions of the AT&T publication "Bell Telephones in Principal Cities" (AT&T 1915) to measure telephone penetration in U.S. cities with population ≥50,000 from 1915 to 1940, including counts of business, residential, and pay phones. We will return to these data in Section 5. We also measure city-level operator unions and operator strikes. We obtain data on local union chapters from two union publications, the Journal of Electrical Workers and Operators (IBEW 1915) and the Union Telephone Operator (IBEW 1921), which list telephone operator union chapters. The first chapter (Local 1A) was chartered in Boston in 1912, and by 1921, there were over 160 active chapters across 31 states. We measure operator strikes using the Annual Reports of the U.S.

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[9] From our newspaper-based data collection effort, which covers newspaper issues between 1917 and 1940, we identify 887 cities and towns with cutovers, of which 676 are known or approximated to have had their first cutover before April 1, 1940 (the 1940 census). The AT&T administrative data (with manual updates) identify 126 cities with a cutover by this date. The two sets largely overlap. Their union nets 688 cities with a cutover by the 1940 census. See Appendix B for complete details of the data collection effort.

[10] To be clear, the complete count census data do not identify employers—only occupations and industries. Recognizing AT&T had a majority national market share throughout this period (Table 1), and was especially concentrated in cities, we treat AT&T as synonymous with the telephone industry in our sample.

Secretary of Labor (U.S. Department of Labor 1913), which report labor disputes, and written histories by Norwood (1990) and Segrave (2017). Between 1900 and 1920, there were nearly one hundred operator strikes around the country, several of which involved coordinated walkouts across many or all cities in a single state or region.[11] We exclude these latter cases and identify a city as having had a strike only if explicitly listed as a striking location.

Of the 3,027 cities in the census data, 415 are identified in our cutover data (384 with exact or approximate timing), and 335 of these have their first cutover before April 1, 1940. In our analysis we exclude 31 cities with ambiguous cutover timing and New York City boroughs, reducing the city sample to 2,992 cities, of which 332 have their first cutover before the 1940 census.[12] In addition, 143 of the 2,992 cities in our final sample we can identify as having had an operator union chapter, 52 cities an operator strike before 1920, and 25 cities with both.

Geographic scope of diffusion

Figure 2 maps all cities with dial cutovers in our newspaper data through 1915, 1920, and so on up to 1940, with bubble sizes corresponding to the number of cutovers to-date.[13] Through this figure, we can effectively see automation taking place in telephone service areas around the country. Although our coverage is limited to cities and regions with newspapers in our data sources, their collective reach is broad. The implied fraction of the U.S. population exposed to dial in 1940 (i.e., living in a city with at least one cutover) is roughly 53%, in the same neighborhood as the 56% of Bell exchanges which were on dial at the end of 1939.[14] We will be exploiting this panel variation for the remainder of this section and in Section 5.

[Figure 2 about here]

4.2 Empirical evidence

We first use these data to identify correlates of automation, relating it to market characteristics. Table 2 shows average 1910 characteristics of cities which had their first cutover before 1920, after 1940, and in five-year intervals in between. The characteristics shown in this table include the adult

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[11] Examples of coordinated regional walkouts include Oregon and Washington in October 1917; all of New England in April 1919; or California, Oregon, Washington, and Nevada in June 1919.

[12] We omit New York City because we often cannot discern the precise borough in newspaper articles on area cutovers, and because the Bronx is grouped with Manhattan in the 1910 census data.

[13] These data include independents' cutovers, as it is often difficult to distinguish Bell and non-Bell cutovers in the data. As previously discussed, the vast majority of telephone service in this sample was provide by AT&T operating companies, and we have strong reason to believe that after 1919, these are mostly AT&T cutovers.

[14] The completeness of the newspaper data can also be evaluated in terms of the number of cities in the AT&T sample which appear in the newspapers sample with known cutover timing (114 of 126), and the number where the earliest cutover in the newspaper data matches or precedes that in the AT&T data (109 of 126).

population; the fraction of this population working and working as operators; the same for young, white, American-born women specifically (age 16 to 25, with shorthand "f/n/w/y"); and indicators for pre-1920 operator unionization and strikes. The most striking pattern is that cities with earlier cutovers are much larger than those with later cutovers, particularly in the AT&T cutover era. The table also indicates that cities with earlier cutovers were substantially more likely to have had an operator union or a strike prior to 1920. These patterns are consistent with the aforementioned discussion of economies of scale, complexity, and wage pressures.

In Table 3 we evaluate these patterns in a multivariate context. We estimate the following cross-city regression, while controlling for state fixed effects (α_s):

$$\mathrm{Y}_i = \mathbf{X}_i\beta + \alpha_s + \varepsilon_i \tag{1}$$

where i indexes cities. In Panel (A) we regress an indicator for pre-1940 cutovers (Columns 1-2) and the timing of a city's first cutover (in decimal years, Columns 3-4) on these same characteristics, now measuring population in logs instead of levels. The strongest predictor of automation remains city size, and unionization is statistically related to cutover presence, though not timing. Panel (B) runs these regressions for 1910-1920 changes, rather than levels, restricting to cities which had their first cutover after 1920. We find qualitatively similar patterns: cutovers correlate with population growth and unionization (in this case, also vis-à-vis timing).

[Table 3 about here]

The magnitudes of these effects are notable. On average, a doubling of population is associated with a 12.5% higher probability of mechanization before 1940, though this disguises a significant nonlinearity: of the largest 50 cities in our sample in 1910, 98% were partially or fully mechanized by 1940, but this rate drops to 79% for cities ranked 51-100, 31% for those ranked 101-500, and 7% among smaller cities. Unionization is associated with 10% higher odds of mechanization by 1940. Strikes have an independent effect of similar magnitude, though only marginally significant at the ten percent level and not significant at the five percent level.

Interestingly, Table 3 does not indicate a statistically significant relationship between cutovers and young women's employment in telephone operation pre-1920, which implicitly measures how much of this labor pool AT&T employed. In Appendix D, we take an event study approach to evaluating this relationship, which the variation supports.[15] With this lens, we see that telephone operation's share of young women's employment was growing rapidly prior to cutovers, with a 20% increase in

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[15] We can do the same for population growth, but not unionization, as operator unions fizzled with the emergence of a company union in the 1920s. Event studies on population are consistent with Table 3.

the employment rate relative to its pre-period level. Changes in the share of young women in the labor force more broadly were not statistically related to cutovers, and magnitudes are small relative to base levels. This suggests labor market tightness in the broad sense did not drive automation, but rather AT&T's own growing demand for operators did.

5 Automation and Firm Growth

Although it decimated telephone operators, automation was seen by AT&T as necessary to support its continued growth. Whether this was true is not only essential to understanding AT&T's return on investment, but also the impacts of technology on concentration. If the largest firms have the greatest incentive to automate, and automation causes firms to grow, increasing returns to scale can lead to winner-take-all economies (e.g., Autor et al. 2020). Although AT&T operated for most of the post-1920 period as a regulated monopoly, for reasons related to high fixed costs and network externalities, The effects of this technological change can nevertheless shed light on how automation affects firm growth, and by implication industry structure—including in the market where, in the early years of the dial era, telephone service was still competed.

To study this question, we use the annual, city-level data from AT&T (1915). These data measure annual telephone stations in cities with ≥50,000 population, with a breakdown of business versus residential phones and an estimate of the size of the service area. We estimate an event study for local telephone industry growth around cutovers (see Appendix Equation D.1). Our sample spans 1915 to 1940, and we restrict to cities with ≤100,000 population in 1920 (as before) and with ≥20 years of data, to ensure an approximately-balanced panel.

Our findings are most easily conveyed graphically. Figure 4 shows event study estimates for the change in business telephones and residential telephones around cutovers, with 95% confidence intervals. We estimate the effects in levels (rather than logs) because bottlenecks were a function of the number of subscribers in a city. In Panel (A), we see that modest growth in business telephones both preceded and followed mechanization. In Panel (B), we see stronger evidence that mechanical switching specifically contributed to the growth of AT&T's residential network, with no discernable pre-trends and significant, sustained growth post-cutover. Panels (C) and (D) show similar results for telephones per capita. Relative to the 1919 values for cities of this size, the point estimates imply >50% 10-year growth for the average city in the sample.

[Figure 4 about here]

Yet as the broader history of the industry shows, automation alone was not a sustainable source of competitive advantage. Independent telephone companies were among the first to adopt mechanical switching, and many did so long before AT&T began its mechanization. The motivations varied by firm, but as Lipartito (1994a) points out, none ever came close to challenging AT&T. The main reason was because AT&T controlled the long-distance network and the largest urban markets, which added value to its other local operations and made other service providers dependent on interconnection, which AT&T could negotiate on its own terms. Competitive advantage derived from the *system*, and how mechanical switching interleaved with it—*not from the technology alone*. This returns us to the most important lesson of this paper: automation was not on its own a sustainable source of advantage in the telephone industry, as its value derived from its complementarities with other assets and activities in AT&T's production system.

6 Explaining the Long Tail

With company documents and data through 1940, we can distill the forces which delayed then propelled automation up to the eve of World War II. But the mechanization of the telephone network was not completed for nearly another forty years. Why was this such a prolonged undertaking? Although we cannot answer this question empirically, our findings thus far provide groundwork of a theoretical foundation that we can use to understand the long tail.

We can begin by observing that automation, as typically understood, is a fixed cost (FC) investment to reduce variable production costs (VC)—with economies of scale intrinsic to the firm's problem. Concretely, a firm producing N widgets under an existing manual technology with constant marginal costs will have $VC(N) = aN$, where $a > 0$. We can characterize an automated technology as having $a' < a$, which also costs k to purchase or develop. If total costs $FC+VC = k+a'N < aN$, i.e. if unit costs $\frac{k}{N} + a' < a$, then automation is a profitable investment. By design, larger firms will be more likely to invest in automation due to economies of scale.

The distinguishing feature of a telephone network (and other networks) is that marginal costs are not constant, but rather increase in the size of the network, being a function not of the number of users, but rather the possible connections between them. To account for this, we can generalize the variable cost function to $VC(N) = aN^X$, where $X > 0$ is a constant; when $X > 1$, marginal costs are increasing in N, and when $X < 1$, they are decreasing. A second distinguishing feature is that costs grow more quickly than marginal product—and in fact the marginal product of network growth is slowing in network size—because the last subscriber adds relatively little value (in the form of new connections) to existing ones (who already enjoy a large stock).[16]

With N subscribers, a telephone network has $\frac{N(N-1)}{2}$ potential connections. If the cost of manually servicing each connection is a, the effect of adding an additional $(N+1)$th subscriber is to introduce N new possible connections, at cost aN; in other words, marginal costs increase linearly in the

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[16] Put differently: if marginal cost is constant in the number of potential connections, but consumers' marginal utility is declining as the network grows, costs can quickly eclipse added value.

network size. We can thus characterize $VC(N)$ for a telephone service company to be approximately quadratic in N, with $VC(N) = a \cdot \frac{1}{2}N^2$. Mechanical switching is still a technology that reduces a (to a'), but in this case, it is interpreted as reducing not the cost of adding a new subscriber per se, but rather of each new *connection* adding that subscriber creates. Total variable cost savings between the manual and automated production technologies are $(a - a')\frac{N^2}{2}$, and just like costs themselves, these cost savings increase quadratically in firm size. As a result, the largest firms will experience dramatically larger savings from the new technology.

The final piece to consider is how the technology changes over time. Let us now characterize a production technology as $a = a(t) = \frac{1}{1+bt}a_0$, where a_0 is the baseline (first-generation) marginal cost and the process $a(t)$ characterizes how that cost declines over time as the technology is improved over time (t). When $b = 0$, the technology experiences no improvements; when b is large, marginal costs fall quickly to zero. Let us now denote the manual and automatic technologies as having $a_1(t)$ and $a_2(t)$, respectively, with associated baseline levels $a_0^1 > a_0^2$, and for the sake of exposition let us assume that $b = 1$. Even if a were linear in t, it would take a much longer time for the productivity benefits of automation in smaller markets to match that achieved quickly by larger markets, by virtue of the fact that the variable cost benefits to automation grow so quickly in market size. If, as written, improvements slow over time (e.g., due to decreasing returns to R&D), then the lags in adoption by firms in large versus small markets will be even greater.

Thus, economies of scale vis-à-vis fixed costs were not the only force making automation relatively more attractive to firms in large markets: even more important is the fact that marginal costs grew rapidly in the size of the firm, compounding the cost savings. This on its own might explain lags in adoption by telephone companies in large and small markets. When technology improvements also slow over time, these adoption lags are likely to grow even larger.

Viewed through this lens, how should we interpret the long tail in Figure 1? If the vast majority of the population lived in high density areas, then this explanation would be moot, because large markets would cover the population. In 1940, however, 43.5% of U.S. residents lived in rural areas, and even in 1980, this fraction was >25%. The long tail of diffusion is thus a result of the confluence of the sheer number of small markets, and the large differences in the returns to automation in large versus small markets. Indeed, when the last manual exchange on Catalina Island was mechanized in 1978, the island was home to approximately only 2,000 people.

7 Discussion and Conclusion

Despite the advantages that AT&T seemingly had as a candidate for mechanization, it was both late and slow to mechanize telephone call switching. We argue that telephone operators were the central nervous system of the entire AT&T business, and the tight web of interdependencies in this system made replacing them an intricate organizational undertaking. Once automation of the AT&T network got underway, scale economies largely explain its procession thereafter—which automation only reinforced by contributing to AT&T's continued growth. These results provide fresh nuance on the organizational barriers and returns to automation at large firms. They also demonstrate a deliberate strategy for spreading successful organizational complements to technology, with implications for understanding the value of multi-business firms.

We believe these findings generalize to modern settings. One of our core contributions is highlighting the depth of changes required to adopt labor-saving technology when labor is central to production. We label this category 'integral' technology, for the many ways it must be integrated with the firm in order to preserve or create value. In complex production environments, this can be a significant obstacle to automation, as we argue above. An example of only partially successful automation is in mail processing, which has been in progress for roughly 60 years. Looking ahead, future examples may include retail sales or warehouse work. Our other findings—that automation reacts to scale and labor market conditions, catalyzes changes in skill demand, and contributes to long-run firm growth, reinforcing market concentration—also seem general.

The historical setting is nevertheless distinctive in that AT&T was a regulated monopoly. Not only did AT&T's operating companies face little competition in most markets, but changes to telephone rates also required regulatory approval, and were set on a rate-of-return basis. Given that a fixed rate of return was ostensibly baked into prices, a natural question which is also important to external validity is why AT&T automated call switching at all.

The primary reason was that AT&T was running up against the limits of manual operation, and rate increases were only a stopgap solution. But a second reason involves the rate-setting process itself. Because telephone service involved many layers of fixed costs (at the system, exchange, line, and individual call levels, with the residual being the length of each call), and some of these costs crossed state boundaries, rate-setting was a complex accounting problem—especially since local and long-distance service were provided through the same exchanges but prices were independently regulated. Mueller (1997) observes that AT&T sought to shift fixed costs to more strictly-regulated jurisdictions as a basis for higher rates, and otherwise keep rates high in its laxer jurisdictions. Through this regulatory arbitrage, AT&T could allocate the fixed costs of automation to local rates governed by relatively-stricter state regulators. In this way, it retained an incentive to invest in marginal cost-reducing innovation. Put briefly, lax interstate regulation coupled with AT&T's ability to cross-subsidize local and long-distance service restored its profit motive. Consistent with this interpretation, many of the newspaper articles from which we collected our data mentioned that dial cutovers were accompanied by local rate increases, as telephone companies requested to price the cost of automatic switching equipment in local rates.

The effects of AT&T's market power are less clear-cut, and an interesting, unanswered question is how the presence of competition from independents in select markets may have affected AT&T's decision to automate local exchanges. Competition could conceivably operate through both demand channels (competing to provide better service) and supply channels (competing for the same workers), and merits further study. Research on the relationship between product market competition and innovation has a long history, but the link between competition and *automation* is ripe for further attention (e.g., Bennett 2020, Macher et al. 2021).

Notwithstanding any concerns about the distinctiveness of AT&T itself, its sheer size as America's largest employer for much of the 20th century makes it inherently important. With increasing concentration in the product and labor market today, especially among firms like Amazon which put many jobs at risk of automation, understanding the causes and consequences of automation at the world's largest employers is increasingly important. Seen in this light, AT&T in the 20th century may offer many lessons for the Amazons of the future.

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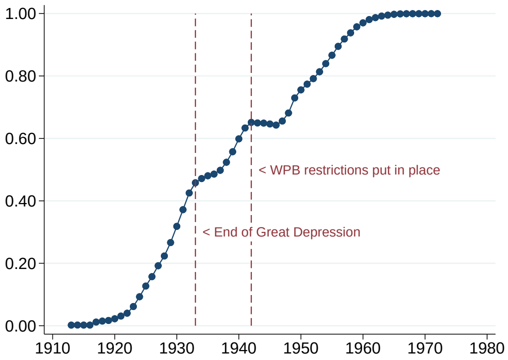
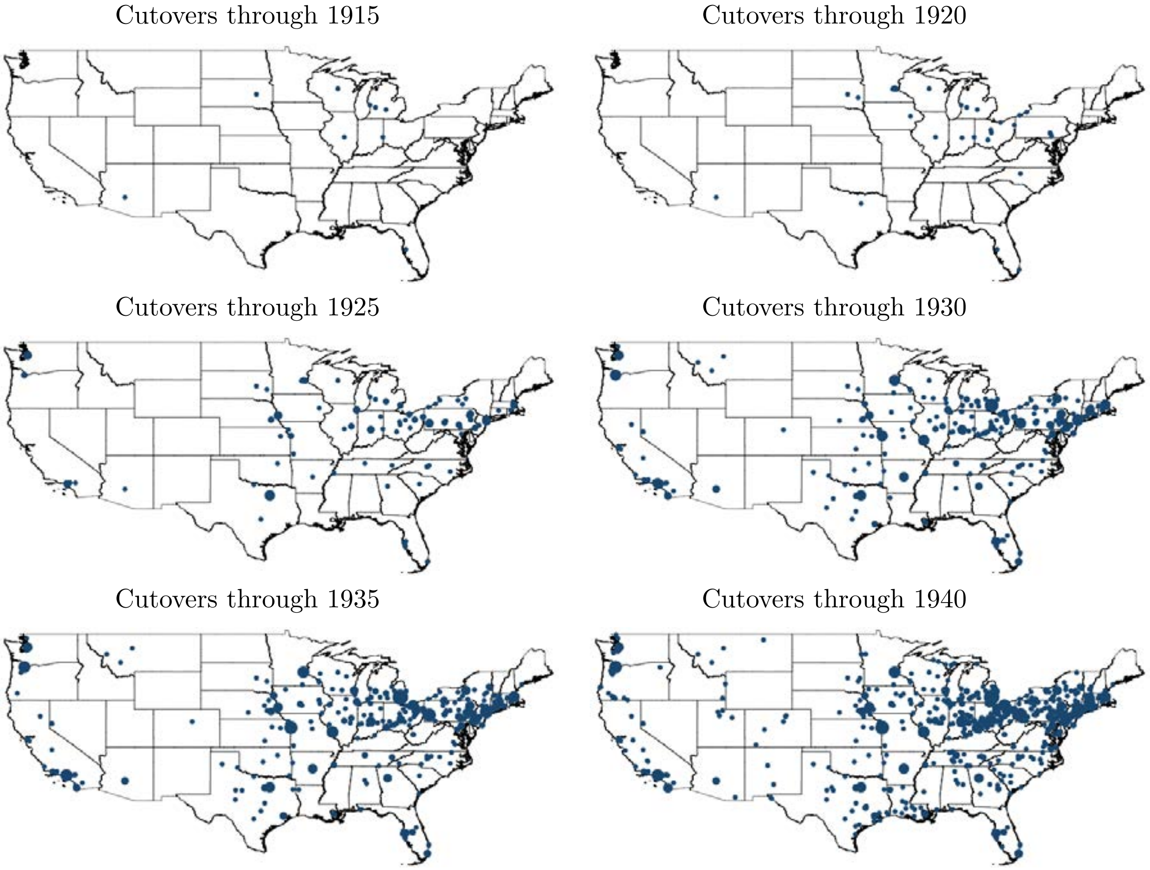
Figure 1: Percent of Bell system on dial, 1913-1972



Notes: Figure shows the fraction of Bell system telephones with mechanical operation (i.e., dial) over time. Data from “Bell System Distributions of Company Telephones,” AT&T Archives and History Center, box 85-04-03-02.

Figure 2: Cities with cutovers in Newspapers data, in 5-year intervals, 1915-1940
bubble sizes proportional to number of cutovers


Cutovers through 1915

Cutovers through 1920

Cutovers through 1925

Cutovers through 1930

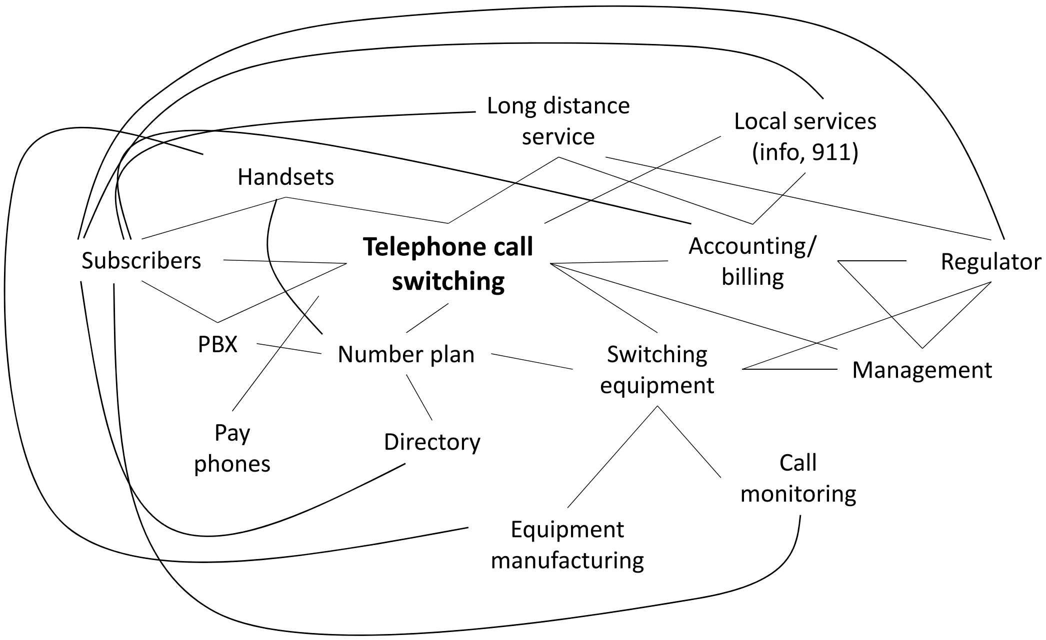
Cutovers through 1935

Cutovers through 1940

Notes: Figure maps the cities with a dial cutover in the newspapers data through each of the given years. Bubble sizes are proportional to the # of reported cutovers through the given year.

Figure 3: Integrating automation into the AT&T production system

Panel (A): Example interdependencies in the AT&T system



Panel (B): Major activities and changes required to adapt this system to mechanical switching

AT&T Corporate
–Develop + test equipment
–Equipment mfg. at scale
–Educate operating company managers on the tech
–Make data-driven recommendations for adoption
–Integrate w/ AT&T Long Lines, other markets

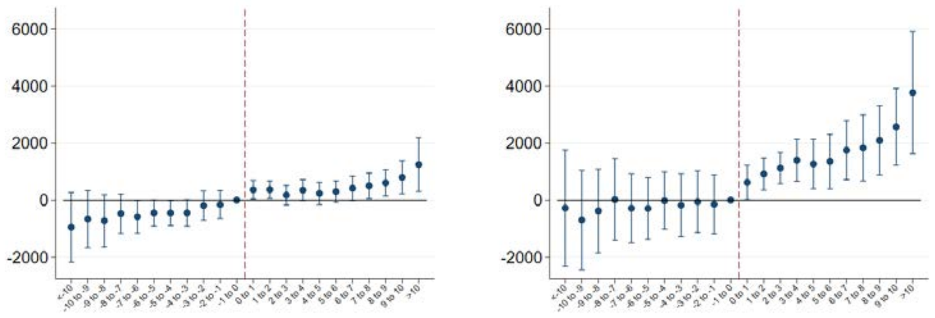
Regulators
–Telephone rate changes
–Public concerns

Central Offices
–Install equipment
–Re-wire exchange
–Integrate with manual
  –Auto-manual boards
  –Traditional operator (contingent labor)
–New approaches to:
  –Information services
  –Emergency services
  –Call monitoring
  –Caller assistance
–Personnel challenges:
  –Labor management
  –Transitional labor
  –New maintenance staff, training, processes
–New building design
–New cost accounting

User Behavior
–User acceptance of dial
–User training on dial
  –On-site training
  –Media campaigns
–Changes in organization (e.g., secretaries)
–Integration w/ PBX

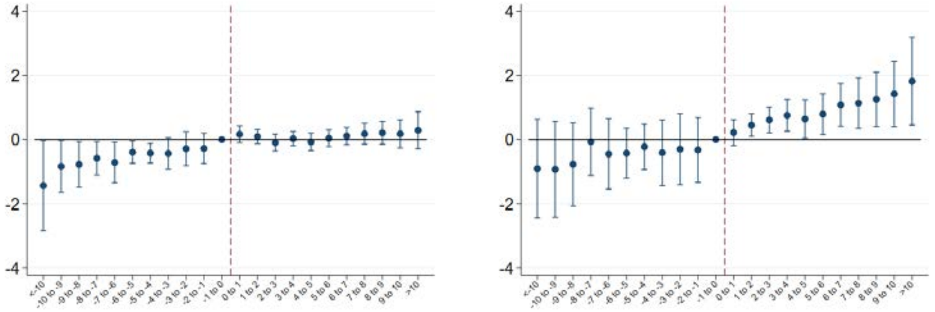
User Technology
–New handsets, w/ dial
–New numbering plans
–New telephone directories
–Method for mapping alphanumeric IDs to a fully-numeric dial

Figure 4: Local telephone industry growth before/after dial cutovers (event study)



Panel (A):
No. of business telephones (units)

Panel (B):
No. of residential telephones (units)



Panel (C):
Business telephones per 100 pop.

Panel (D):
Residential telephones per 100 pop.

Notes: Figure presents results of event study regressions estimating local Bell System growth cutovers, using data from (AT&T 1915). Sample restricted to cities with at least 20 years of data and with population ≤100k in 1920, where cutovers were typically one-time events. All specifications control for the size of the local service area. Error bars represent 95% confidence intervals, computed from SEs clustered at the city level.

Table 1: Characteristics of U.S. telephone industry, 1902-1932

	1902	1907	1912	1917	1922	1927	1932	1937
Growth of industry								
Miles of wire (1000s)	4,900	12,999	20,248	28,827	37,266	63,836	87,678	90,831
Telephones (1000s)	2,371	6,119	8,730	11,717	14,347	18,523	17,424	19,453
Telephone calls (MMs)	5,071	11,373	13,736	21,846	24,648	31,614	30,048	33,618
Telephone calls (per capita)	64	131	144	212	224	266	241	261
Employees	78,752	144,169	183,361	262,629	312,015	375,272	334,085	333,162
Male				91,510	104,433	131,802	128,677	129,722
Female				171,119	207,582	243,470	205,408	203,440
Labor productivity								
Employees per MM calls	15.53	12.68	13.35	12.02	12.66	11.87	11.12	9.91
Male				4.19	4.24	4.17	4.28	3.86
Female				7.83	8.42	7.70	6.84	6.05
Market share								
AT&T share	56%	51%	58%	63%	66%	74%	79%	79%

Notes: Data from U.S. Census of Electrical Industries, 1902-37 (U.S. Census Bureau 1902). Sample covers all Bell and independent operating companies. Call volume and employment data for 1912 are restricted to companies with >\$5000 in income (1912 dollars) and thus slightly understated.

Table 2: Average 1910 characteristics of cities by timing of earliest cutover

		AT&T cutover era				
Characteristic	pre-1920	1921-1925	1926-1930	1931-1935	1936-1940	post-1940
Population 16+ (1000s)	38.92	116.82	43.87	18.41	9.14	4.06
	(55.49)	(248.98)	(80.23)	(27.30)	(13.33)	(6.68)
Percent working	60.54	60.35	60.81	59.60	58.96	57.55
	(5.27)	(5.05)	(5.69)	(5.64)	(5.83)	(7.28)
Percent operators	0.19	0.21	0.19	0.17	0.19	0.21
	(0.10)	(0.12)	(0.14)	(0.11)	(0.11)	(0.15)
F/n/w/y percent working	41.17	40.68	40.23	44.01	36.71	35.09
	(7.79)	(12.09)	(10.32)	(11.86)	(12.31)	(12.12)
F/n/w/y percent operators	1.16	1.36	1.19	1.02	1.12	1.21
	(0.65)	(1.09)	(0.87)	(0.67)	(0.79)	(0.97)
Unionized by 1920	0.17	0.26	0.19	0.09	0.08	0.03
	(0.38)	(0.44)	(0.40)	(0.29)	(0.28)	(0.18)
Had strike by 1920	0.07	0.10	0.09	0.03	0.03	0.01
	(0.26)	(0.30)	(0.28)	(0.17)	(0.18)	(0.11)
Observations	29	62	114	67	60	2660

Notes: Table reports mean 1910 characteristics of cities in our primary sample whose first cutover occurred in each of the periods shown (2,992 cities included in this table, omitting 31 cities with cutovers with ambiguous timing and New York City boroughs). Population and population percentages reflect the adult (16+) population only, and f/n/w/y are shorthand for female, native-born, white/non-Hispanic, and young (age 16-25). The final column consists of cities that do not have a cutover in our data by April 1, 1940. Standard deviations in parentheses.

Table 3: Relationship of 1(Any cutover) and cutover timing of earliest cutover with city characteristics

Panel (A): Cutovers and city characteristics, 1910

	Any cutover by 1940? (1)	(2)	Timing of earliest cutover (3)	(4)
Ln(Population 16+)	0.125**	0.123**	-1.639**	-1.757**
	(0.007)	(0.007)	(0.208)	(0.221)
F/n/w/y pct. working		0.001		0.047
		(0.001)		(0.043)
F/n/w/y pct. operators		-0.004		-0.275
		(0.006)		(0.373)
Unionized by 1920	0.105**	0.105**	-2.271	-2.332
	(0.036)	(0.036)	(1.285)	(1.282)
Had strike by 1920	0.100	0.103	0.859	0.973
	(0.054)	(0.054)	(1.584)	(1.587)
N	2992	2992	332	332
R^2	0.25	0.25	0.32	0.32
Y Mean	0.11	0.11	1929.08	1929.08

Panel (B): Cutovers and Δ in city characteristics, 1910-1920

	Any cutover by 1940? (1)	(2)	Timing of earliest cutover (3)	(4)
Δ Ln(Population 16+)	0.050**	0.049**	-2.609**	-2.585**
	(0.015)	(0.015)	(0.910)	(0.924)
Δ F/n/w/y pct. working		0.001		-0.039
		(0.001)		(0.053)
Δ F/n/w/y pct. operators		0.007		-0.296
		(0.004)		(0.294)
Unionized in 1910s	0.281**	0.280**	-3.136**	-3.168**
	(0.042)	(0.042)	(0.916)	(0.903)
Had strike in 1910s	0.158	0.155	-0.691	-0.575
	(0.088)	(0.089)	(2.680)	(2.682)
N	2966	2966	306	306
R^2	0.09	0.09	0.21	0.22
Y Mean	0.10	0.10	1930.27	1930.27

Notes: Table reports estimates from a regression of an indicator for whether a given city has a cutover in our data by April 1, 1940 (Columns 1 to 2) and the timing of the earliest cutover (Columns 3 to 4) on city characteristics in 1910 (Panel A) and changes in city characteristics from 1910 to 1920 (Panel B). The sample for all columns omits cities with a cutover before the 1920 census or ambiguous cutover timing and New York City boroughs. The latter columns are further restricted to cities with a cutover between 1920 and 1940. Population and population percentages reflect the adult (16+) population only, and f/n/w/y are shorthand for female, American-born, white/non-Hispanic, and young (age 16-25). * and ** represent significance at the 0.05 and 0.01 levels, respectively. All specifications include state fixed effects. Robust SEs in parentheses.

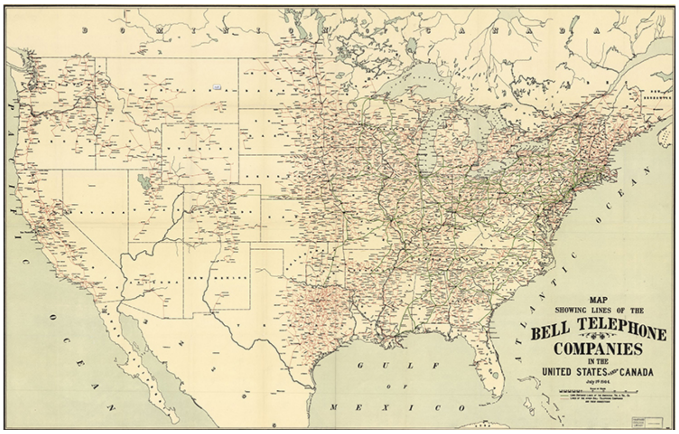
Web Appendix

A Historical Appendix

Figure A.1: Bell System maps, 1891 to 1909

1891 1898

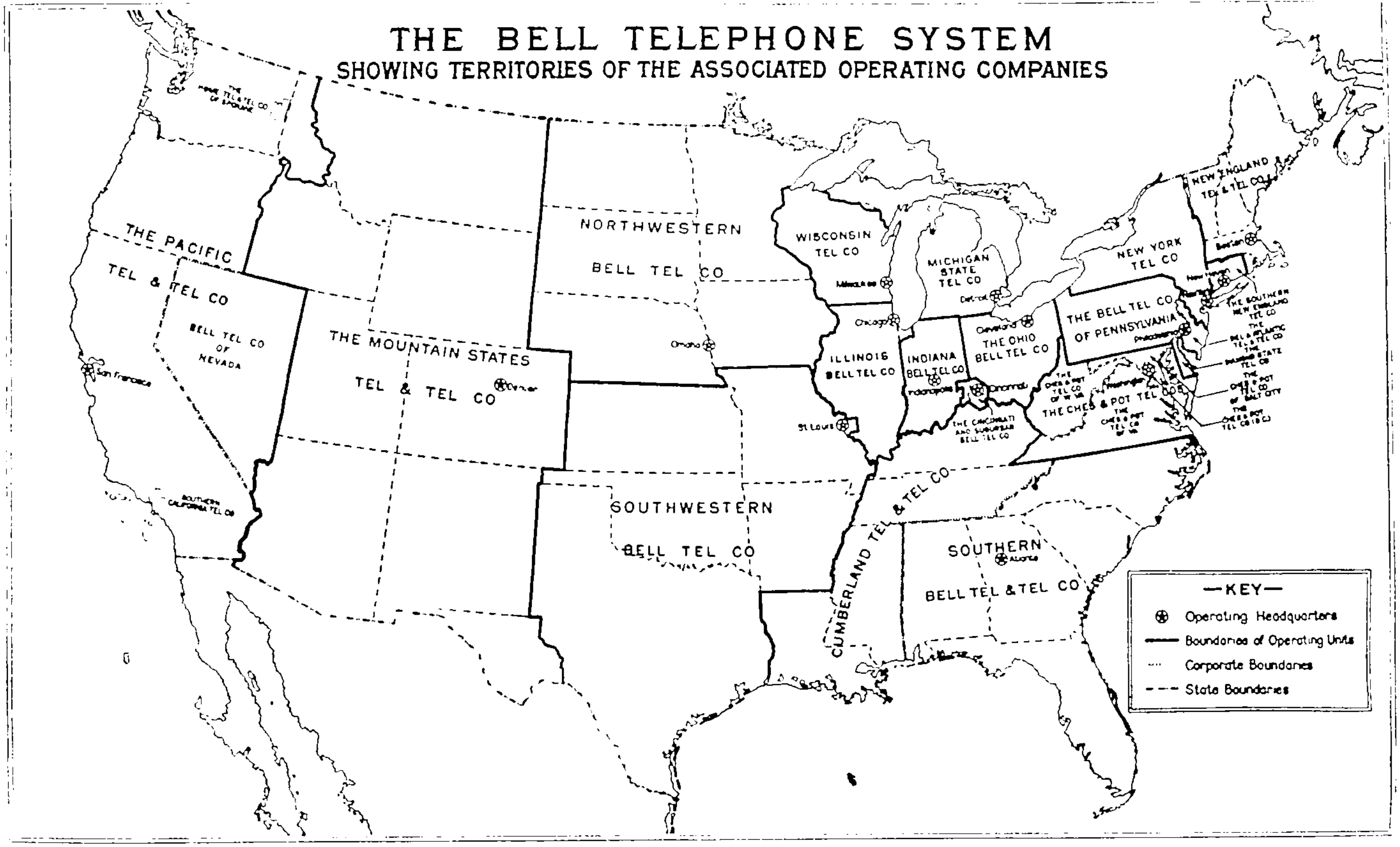
1904



1909

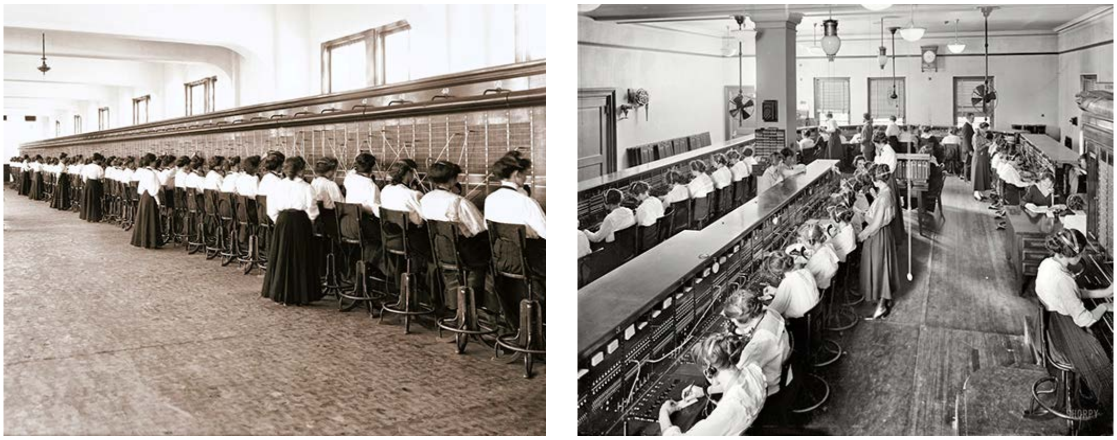
Notes: Figure uses national Bell System maps to illustrate the expansion of the AT&T network from 1891 to 1909. Images obtained from the Dave Rumsey Map Collection.

Figure A.2: Map of the Bell regional operating companies, from AT&T's 1922 annual report



Notes: Figure marks the boundaries of the various Bell operating companies' territories across the united states, and the headquarters city for each. Map from AT&T's 1922 annual report.

Figure A.3: Photographs of switchboard operators



Salt Lake City, UT, 1913

Washington, DC, 1919

Unknown location, 1943

Notes: Figure shows photographs of telephone operators at switchboards.

B Data Appendix

Note: This appendix closely parallels (and at times replicates) the data appendix of Feigenbaum and Gross (2021), "Automation and the Future of Young Workers: Evidence from Telephone Operation in the Early 20th Century," which studies the effects of mechanical switching on the labor market for young women. Both papers use the same data sources to measure cutovers, and the same census data to measure population patterns around cutovers.

B.1 Data on dial cutover location/timing

We collect data on the local adoption of mechanical call switching (dial) from two sources: records at the AT&T archives which report dial penetration in cities with population >50,000 in the 1930s, and local newspaper reports, which cover cities large and small across the country.

To understand the cutover data collection it is useful to first recall the process by which cutovers took place. Although the AT&T corporate office (specifically, AT&T's chief engineer) gave general guidance to the regional operating subsidiaries on the adoption of dial—including information on the performance of dial vs. manual operation in different-sized markets and under different operating conditions—the decision to convert any single telephone exchange from manual to dial was made by the management of the operating companies themselves. This decision would set in motion a multi-year planning and installation process: exchange buildings had to be expanded or built, new switching equipment had to be installed, and new telephone directories and dial telephone sets had to be distributed to subscribers, who in turn had to be taught how to use them when dial service began. Judging from the newspaper reporting which we describe below, the date that telephone service would convert to dial was fixed in advance, but sometimes experienced (usually modest) delays. On the designated day—usually at midnight on a Saturday, when call volumes were lowest—technicians would physically cut the wires out of the manual switchboards, and connect them to the mechanical equipment (hence the term "cutover"). The actual cutting-over took only a few minutes, after which local calls were mechanically operated. In small cities and rural areas with at most a few telephone exchanges, these would typically all be cut over together. In larger cities with many to hundreds of telephone exchanges (New York had hundreds), these conversions effectively took place one exchange/neighborhood at a time, such that in these cities, telephone service was automated in a more piecemeal fashion over years or decades.

Data from AT&T's corporate archives

Because AT&T cutover decisions were decentralized, there is no single source at the AT&T archives documenting the place and time of all cutovers in the Bell system.[1] However, in the course of reviewing documents at the AT&T corporate archives (Warren, NJ), we discovered a three-page document compiled in the late 1930s which lists all cities in the U.S. and Canada with population

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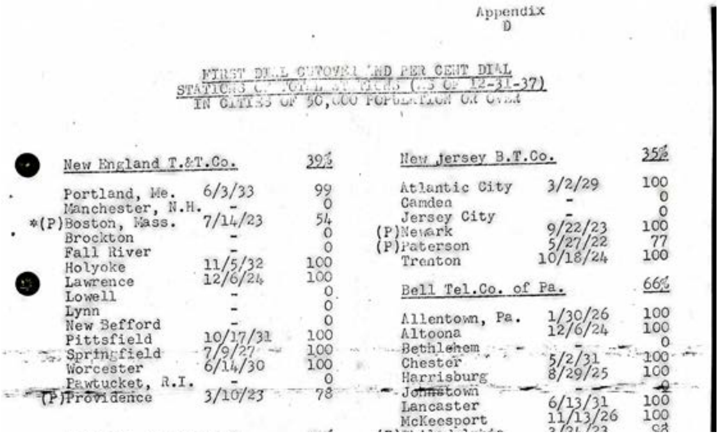
[1] According to a call with Sheldon Hochheiser, AT&T corporate historian, on March 1, 2017, the decision and pace of dial adoption was decided by management of the individual regional operating companies, not AT&T corporate.

>50,000, along with the date of that city's first cutover to dial and the percent of subscribers on dial as of December 31, 1937 (Figure B.1).[2] For cities which were less than 100% dial in 1937, we manually search Google and historical newspapers for reports of cutovers between 1937 and 1940, and update the percent dial to 1940 values based on these results.

Figure B.1: AT&T data on the adoption of dial in cities of population >50,000



Appendix
D

FIRST DIAL CUTOVER AND PER CENT DIAL
STATIONS [illegible] (AS OF 12-31-37)
IN CITIES OF 50,000 POPULATION OR OVER

New England T.&T.Co.		39%
Portland, Me.	6/3/33	99
Manchester, N.H.	-	0
*(P)Boston, Mass.	7/14/23	54
Brockton	-	0
Fall River	-	0
Holyoke	11/5/32	100
Lawrence	12/6/24	100
Lowell	-	0
Lynn	-	0
New Befford	-	0
Pittsfield	10/17/31	100
Springfield	7/9/27	100
Worcester	6/14/30	100
Pawtucket, R.I.	-	0
(P)Providence	3/10/23	78

New Jersey B.T.Co.		35%
Atlantic City	3/2/29	100
Camden	-	0
Jersey City	-	0
(P)Newark	9/22/23	100
(P)Paterson	5/27/22	77
Trenton	10/18/24	100

Bell Tel.Co. of Pa.		66%
Allentown, Pa.	1/30/26	100
Altoona	12/6/24	100
Bethlehem	-	0
Chester	5/2/31	100
Harrisburg	8/29/25	100
Johnstown	-	0
Lancaster	6/13/31	100
McKeesport	11/13/26	100

Notes: Figure shows an extracted table from the source data on dial installation in large cities from the AT&T Archives and History Center (box 106-10-02-07).

Figures B.2 and B.3 below provide suggestive evidence that smaller cities in the AT&T data (with population ≤100k) typically had one-shot cutovers, whereas larger cities were converted to dial in a more piecemeal fashion: the smaller cities were nearly all 100% dial by 1940, irrespective of the date of their first cutover, whereas the larger cities show more heterogeneity.

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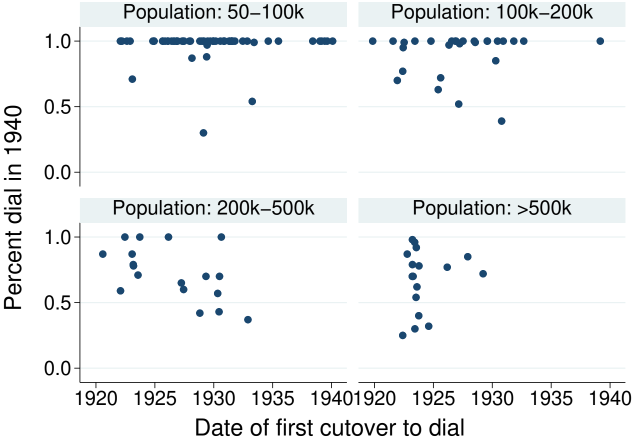
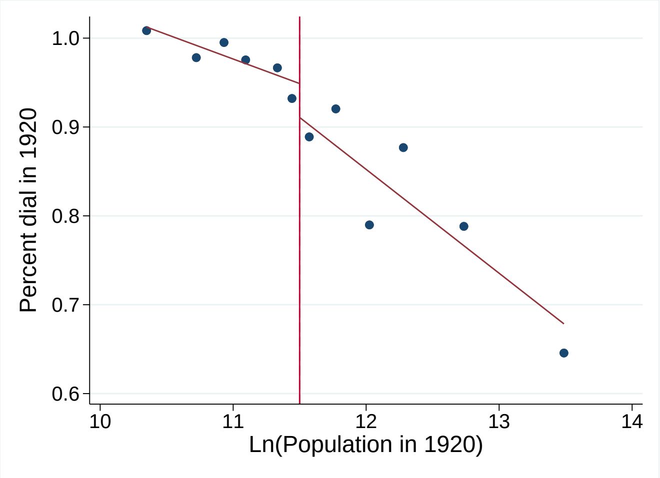
[2] This document was found in AT&T Archives and History Center box 106-10-02-07.

Figure B.2: AT&T city-level data: Fraction dial in 1940 vs. first cutover date



Notes: Figure plots a city's fraction dial in 1940 against the date of the city's first cutover to dial, for cities in the AT&T data, group by their 1920 population. The figure illustrates that smaller large cities (≤100k population) with cutovers were nearly all 100% dial, irrespective of the first cutover date, suggesting that they were single-cutover cities. In larger cities (200-500k), the fraction dial in 1940 varies with how recently cutovers began, and in the largest cities (>500k), which nearly all began cutting over to dial before 1925, they are unrelated.

Figure B.3: AT&T city-level data: Fraction dial in 1940 vs. population



Notes: Figure shows a binned scatterplot of a city's fraction dial in 1940 against its log population, with a trend break at 100k population (the log of which is ≈11.5). The figure indicates that these smaller cities were typically around 100% dial by 1940, irrespective of their size, suggesting that they were single-cutover cities. In larger cities, the fraction dial in 1940 varies inversely with population.

Data from historical newspapers

We supplement the large-city AT&T data with a more comprehensive data collection effort from historical newspapers. Dial cutovers were locally-notable events and often reported on in the days before and after the change, and also sometimes months or even years in advance or later—not only because readers needed to know when to start using their dial telephone sets, but also out of public curiosity or celebration, as well as due to public concern over the fate of soon-to-be disemployed telephone operators, which was itself the focus of many articles.

We searched three online digitized newspaper collections for reports of cutovers and had assistants read through search hits to identify articles which reported cutovers, and for each record the cutover city, date, and number or percent of affected subscribers. Because these data are at the core of the paper, we will describe the data collection in substantial detail.

Round 1: July-August 2017

Data collection efforts began in the summer of 2017 and were initially focused on reviewing articles between 1917 and 1940 at Newspapers.com, which hosts the largest digitized, searchable historical newspaper collection available.[3] After testing several potential Boolean search terms, we settled on two preferred search terms, which we label "ST1" and "ST2" below:

(ST1) telephone ("dial" or "automatic") ("cutover" or "cut over" or "changeover" or "manual") ("office" or "exchange")

(ST2) telephone ("dial" or "automatic") ("cutover" or "cut over" or "changeover" or "manual") "midnight"

Whereas ST2 is a more targeted search (due to the requirement of the word "midnight") and is designed to minimize false positives, ST1 casts a wider net and is designed to minimize false negatives. Between the two, we believe we can identify nearly all cutovers reported in the Newspapers.com collection. When these searches were conducted in July 2017, ST2 returned 4173 results, and ST1 returned 36072 results, of which 33060 were additional to those of ST2.

We had research assistants read all articles in the ST2 search results and the top 25% of the ST1 results[4] and asked them to determine whether the article does in fact describe a cutover, and if so, to record (i) the cities affected (sometimes several neighboring small towns are cut over at once, or served jointly by a single exchange); (ii) the date, including whether past or future (planned); (iii) the number or percent of subscribers affected, if reported (rarely); and (iv) any additional notes that may be relevant to measurement or interpretation (for example, occasionally an article reports on a cutover at a large firm or other organization that operates its own private, internal switchboard, rather than at the local telephone service provider). Whenever a research assistant

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[3] The search window was chosen on the grounds that (i) AT&T records indicate that the firm only began dial cutovers in the late 1910s, and (ii) we have outcome data through 1940.

[4] The search results are listed in order of "relevance", however determined by the website. Reassuringly, the rate of verified cutovers in these search results declines rapidly in the search rank: by the time we get a quarter of a way down the ST1 results list, only around 5 out of every 100 search results is a true description of a cutover, and these are often redundant to earlier reports, or lacking information on timing and unusable.

flagged an article as describing a cutover or potentially describing a cutover, we manually reviewed their data entry to ensure the accuracy of the entered data.

We find newspaper reporting on both past and future cutovers characterized with varying degrees of specificity: many articles report exact dates, but some—especially articles that reference cutovers in passing, but are focused on other telephone company news—describe only the month and year (e.g., "last month"), season and year ("next fall"), year alone ("towards the end of this year"), or are non-specific (e.g., "nearing completion", proposed but not yet planned, or no timing reported; in the cases where an article describes a cutover without providing any information on its timing, we nevertheless infer whether that timing is past or future based on the verb tense in the article). In many cases, we find multiple reports of the same cutover, and we use these to cross-validate and refine our timing measures where possible. We take these data and aggregate up to the city and month: given that we study census-measured outcomes at decadal frequency, monthly variation in cutover timing should be sufficient for the purposes of this paper.

It is important to attempt to include cutovers even with imprecisely-reported timing: dropping these cutovers would bias our results towards zero, as the control group (of cities not cut over by 1940) would then have treated locations in it. Moreover, with outcomes at only decadal frequency, a bit of measurement error on the precise timing is acceptable in specifications that measure treatment as $\mathbb{1}$(Post-cutover) (but specifications measuring the time since a cutover would be more sensitive to this type of measurement error). When a cutover is reported with an "approximate" date, we thus treat it as the true date. If the reported timing is otherwise non-specific, we use the following classification and crosswalk to approximate the month and year:

Category	Timing
ongoing	same month
recent	same month
soon	same month
in_few_weeks	next month
in_few_months	3 months ahead
winter	January of given year
winter_early	December of given year
winter_mid	January of given year
winter_late	February of given year
spring	April of given year
spring_early	March of given year
spring_mid	April of given year
spring_late	May of given year
summer	July of given year
summer_early	June of given year
summer_mid	July of given year
summer_late	August of given year
fall	October of given year
fall_early	September of given year
fall_mid	October of given year
fall_late	November of given year
year_early	March of given year
year_mid	July of given year
year_late	November of given year

When an article provides only the year and no more precise information can be inferred from other reports, we do the following: if the year is in the past or present (relative to the article), we assign the cutover to July of that year (the midpoint). Although this may introduce measurement error, this error will not be material to this paper unless the year is a Census year, and there are only two such cases in the data (one of which is Detroit, a large city, which we exclude from our event study on the grounds of its size anyway). If the year is in the future, the cutover itself is uncertain, let alone the timing, and we treat it as planned but undated.

Round 2: July-August 2019

In the summer of 2019, we undertook a second round of newspaper-based data collection to capture new results from Newspapers.com, whose collection of digitized newspapers had more than doubled, and to expand our data collection effort to the two next-largest digital newspaper repositories (NewspaperArchive.com and GenealogyBank.com), which may cover different cities or time periods. In July 2019, we repeated our ST1 and ST2 searches for the 1917-1940 period on Newspapers.com, and also performed searches on these two additional sites.[5]

When these searches were conducted on Newspapers.com in June 2019, ST2 returned 6666 results, of which 2490 were new since 2017, and 2280 of these unique newspaper issues (in the second

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[5] Note that NewspaperArchive.com does not support Boolean search. In this case, we searched each non-Boolean permutation of each search term. For this data source we skipped the following permutations of ST1: "telephone dial manual office" / "telephone dial manual exchange" / "telephone automatic manual office" / "telephone automatic manual exchange", due to the size of the results list and the high rate of false positives. Having omitted these results, we review all other ST1 results from NewspaperArchive.com (rather than just the top 25%). We believe most true positives in these search results will be picked up this way.

Figure B.4: Example newspaper headlines reporting dial cutovers and job losses

Dial System Supplants Telephone Girls Tonight

Sweet Voiced Operator's "Number Please" Will Be Heard for Last Time Today—Cutover Marks Epoch in Worcester's History

HELLO GIRL SAYS GOODBYE FOREVER AND CITY "DIALS"

Employed 120 Girls

There were approximately 120 girls employed by the Bell Telephone company as operators prior to today. In a few weeks, but half that number will be on the payroll. The rest will have returned to school or will have found other employment. At least half of the force was

Dials Will Replace 500 Phone Girls

New Haven, March 6.—(Special.) —Five hundred telephone operators in the New Haven district, will lose their jobs April 19 when the change from manual to dial telephones here is made. Only 200 girls will be required as switchboard operators in place of the 700 now employed.

Notes: Figure shows examples of headlines from historical newspapers reporting local cutovers. Clockwise from top: *Worcester Telegram*, Worcester, MA, 1930; *Hartford Courant*, Hartford, CT, 1930; *Battle Creek Enquirer*, Battle Creek, MI, 1927.

round of data collection, we noticed that sometimes the search returns multiple hits from the same newspaper on the same day, and we had assistants read each newspaper issue only once, to reduce duplicated efforts). ST1 returned 55312, of which 39889 were also not already collected in 2017 or covered by ST2, 36502 of these from unique issues, and 3512 in the top 25% of ST1 search results. These results (2280 for ST2, 3512 for ST1) were then manually reviewed by research assistants. Similarly: on GenealogyBank.com, ST2 returned 2609 results, of which 2497 were new since 2017, and 2309 of these unique issues; ST1 returned 21171, of which 18143 were also not already collected in 2017 or covered by ST2, 16304 of these unique issues, and 4021 in the top 25% of ST1 search results. On NewspaperArchive.com, ST2 returned 2100 results, of which 1512 were new since 2017, and 1189 of these unique issues; ST1 returned 1520 (see previous footnote as to why this number is lower than that for ST2), of which 828 were also not already collected in 2017 or covered by ST2, 513 of these unique issues. The table below summarizes this information:

			ST2	ST1 (not in ST2)	Total
Round 1 (2017)	Newspapers.com	All results	4,173	33,060	37,233
		Reviewed	4,173	8,265	12,438
Round 2 (2019)	Newspapers.com	New results	2,490	36,502	38,782
		Reviewed	2,280	3,512	5,792
	NewspaperArchive.com	All results	2,100	1,520	3,620
		Reviewed	1,189	513	1,702
	GenealogyBank.com	All results	2,609	21,171	23,780
		Reviewed	2,309	4,021	6,330
	Total	All results	11,372	92,253	103,415
		Reviewed	9,951	16,311	26,262

Results

In total, we find 3,945 reports of cutovers in the continental U.S., with 3,859 describing non-private branch exchange (PBX) cutovers in 887 distinct cities and towns. With respect to the precision of the timing information, these reports break down as follows:

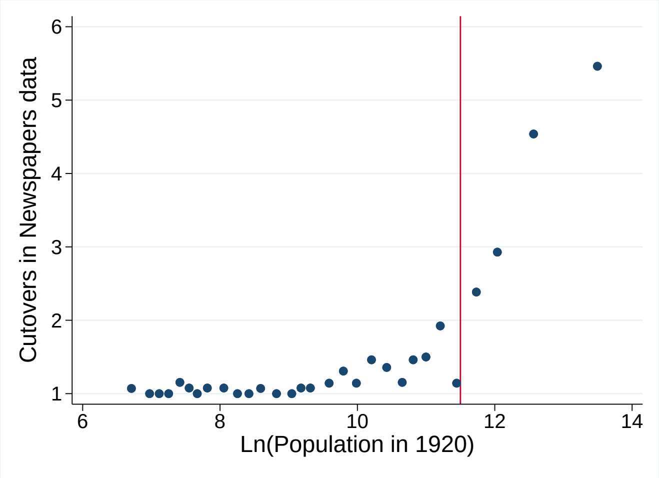
		Articles	
Category	Label	Count	Percent
1	Exact date provided	2,171	56.2
2	Date inferred from coarse information + other reports	1,150	29.8
3	Month and year provided or approximated	308	8.0
4	Year provided, past or present	25	0.7
5	Year provided, future	9	0.2
6	No timing information provided	196	5.1
Total		3,859	100

Of the 887 cities with cutovers, 798 have at least one cutover in the newspapers data with exact or approximate timing (categories 1-4 above), whereas 89 *only* have cutovers without reliable timing information. To be conservative, we drop these cities from the analysis throughout the paper, because we cannot know for certain when the shock occurred—or, for reports of future cutovers, if it even occurred at all. For the remaining cities: although a handful (43) have ≥1 reports of a cutover that we are unable to date, (i) most of these are large cities excluded from the main analytical sample, and (ii) we find that the majority (70%) have their earliest known cutover in the 1920s, and the vast majority (98%) by 1933, providing confidence that we can accurately measure cities' earliest cutovers, which is the relevant margin for this paper.

We aggregate these data up to the city x month level, identifying months in which each city was reported to have experienced a dial cutover, and henceforth we call each such city-month a "cutover" (we assume that when there are multiple reported cutovers in a given city in the same month, these are part of the same event—although there are few such cases in the data, as we have previously harmonized cutover dates in the raw data).

There are 1,047 cutovers with known timing across the 798 cities in our final sample (an average of 1.3 per city, with a median of 1, 90th percentile of 2, and max of 15), and 904 that take place between the 1910 and 1940 Censuses (April 1910 and April 1940), the period studied in this paper. Among these, the average and median cutover took place in 1931.[6] Figure 2 in the paper mapped these cutovers, illustrating their expanding geographic incidence—which is the variation at the heart of this paper. Figure B.5 shows a binned scatterplot of a city's number of cutovers in the Newspapers data against 1920 log population, with a line at 100k population (our threshold for the event study sample). This figure reinforces the evidence that smaller cities typically have only one or at most two cutovers in our data, consistent with these locations being served by only one or a few telephone exchanges, which could be simultaneously converted to dial.

Figure B.5: Newspapers city-level data: Number of reported cutovers vs. 1920 population



Notes: Figure shows a binned scatterplot of cities' number of reported cutovers, measured as the number of distinct months between 1919 and 1940 with a cutover reported in our Newspaper data, against log 1920 population, with a line drawn at 100k population (the log of which is ≈11.5). The figure illustrates that smaller cities typically have only one or at most two cutovers in our data, suggesting that they were single-cutover cities. Larger cities have several cutovers in our data.

Comparison of AT&T and Newspapers data

We can also cross-validate the AT&T and Newspapers data against each other, by comparing the timing of the earliest cutover reported in newspapers versus in the AT&T administrative data for all cities appearing in both sources. Figure B.6 shows this comparison, plotting individual cities' earliest newspaper-reported cutover (vertical axis) against earliest AT&T-reported cutover (horizontal axis). Each point represents a city and is labeled with its state's abbreviation, and the dashed red line is the 45-degree line. Dates coincide across the two sources for the vast majority of cities, providing reassurance on the quality of the newspaper data. For the handful of cities

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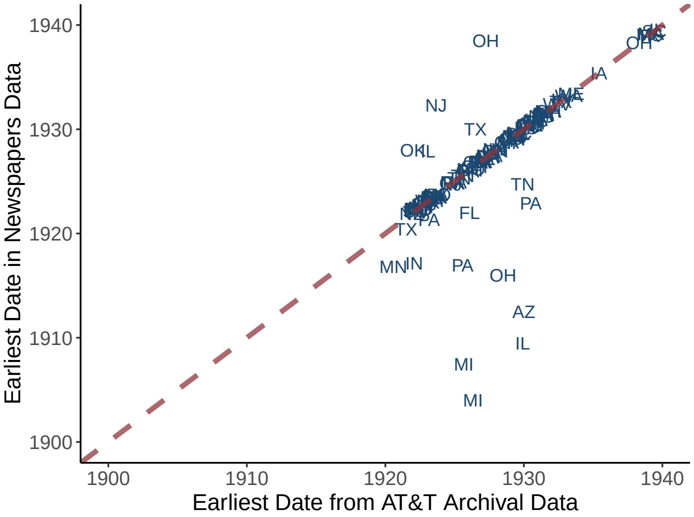
[6] Note that of the 1,047 cutovers with known timing from the Newspapers data, 26 cutovers (2.5%) took place before the first cutover in the AT&T data (in November 1919), ostensibly having been executed by independent (non-AT&T) telephone service providers—which we confirm by manual review. Additional comparisons between AT&T and Newspapers data are provided in the next subsection below.

where newspapers report a cutover preceding those in the AT&T data by more than a month (below the 45-degree line), we revisited the reporting articles and determined that either (i) these were performed by independent (non-AT&T) companies (13 cases), or (ii) these were preliminary cutovers affecting a very small portion of the population (1 case).

Figure B.6: Timing of cities' first cutover in AT&T data vs. newspaper data



Notes: Figure plots cities' earliest observed cutover date in newspapers data versus AT&T data, for cities in both data sources, and the 45-degree line in red. Each city is labeled with its state abbreviation. Figure is presented to illustrate the degree of agreement between the AT&T and newspapers data. Nearly all cutovers identified in the newspaper data collection that preceded AT&T-reported cutovers were performed by independent (non-AT&T) telephone companies.

B.2 Complete-count Census data

Taken decennially, the US Federal Census enumerates the entire population and contains a wealth of economic, social, and demographic information. We draw on the recently digitized complete count census data from IPUMS (Ruggles et al. 2019) for the censuses in 1900, 1910, 1920, 1930, and 1940.[7] That the data is complete count means simply that all individuals enumerated—the complete count of people in the US in each census year—has been transcribed and coded by IPUMS. This enables us to count not just the number of telephone operators in the telephone industry in each city, but also the number of people in other occupations or industries, in any location, or of any particular demographic. In this appendix subsection, we describe the complete count data and our data aggregation procedure, and the variables it yields.

Aggregation of complete count individual-level data

Unit of observation

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[7] We stop in 1940 because the census is privacy-restricted for 72 years after it is taken and so 1940 is the most recent census IPUMS has and could transcribe and digitize in full.

We restrict attention to the adult (16+) non-farm population with non-farm occupations, in the continental U.S. only (lower 48 states plus District of Columbia). Our primary dataset aggregates these individuals in the complete count data up to the level of:

city (continental U.S. only)
x American-born (dummy)
x race and ethnicity (bins)
x sex (dummy)
x age (bins)
x urban (dummy)
x occupation (1950 encoding)
x industry (1950 encoding)
x year (decade)

where these variables are defined as follows:

- American-born: indicates whether an individual was born in a U.S. state or territory
- Race/ethnicity: bins for (i) white/non-Hispanic, (ii) white/Hispanic, (iii) black, (iv) Native American, (v) Asian, (vi) mixed, and (vii) other
- Sex: indicates whether individual is male or female
- Age: 5-year bins for individuals age 16-20 to 56-60, and 61+
- Urban: indicates whether individual's household was urban (vs. rural)
- Occupation: 1950 occupation codes (283 categories)
- Industry: 1950 industry codes (162 categories)

In addition to this city x demographic bin x year datasets, we prepared separate datasets of (i) all individuals reporting as telephone operators (occ1950=370), and (ii) all individuals reporting as working in the telephone industry (ind1950=578).

Sampled cities

The raw complete count data include each individual's household's state and county, and city where relevant. The IPUMS data includes not only a raw city string (as originally reported on Census manuscripts) but also a standardized city, to account for the fact that city spellings may change or be reported slightly differently for different households or in different years. However, this standardized city was not always provided, or was sometimes provided where the raw city was missing, and we determined that additional harmonization was needed.

We begin by combining the list of raw city strings and IPUMS-standardized cities from all years 1910-1940 (note that these can vary: some smaller cities are not found in every year of the IPUMS data). Having done so, we then manually examine (i) cities in the same state that start with the same three letters, (ii) cities in the same county that sort adjacently and have a Levenshtein edit distance of ≤ 4, and/or (iii) cities in the same county that sort within 30 positions of each other and have an edit distance ≤ 2, to find spelling variants that appear to be the same city. We use the results of this effort to build a crosswalk from the raw and IPUMS-standardized city names to our manually, fully-harmonized city names. We apply this crosswalk to both the raw city strings and IPUMS-standardized city names, which will also now match when both are provided. We take either of these measures, when available, as an individual's (household's) true city.

From this effort, we produce a list of unique, harmonized cities by year. We then identify all such cities which (i) are observed every year from 1910 to 1940, and (ii) have a population of ≥2,000 in 1920, as measured by aggregating up individuals in the IPUMS data. This yields a balanced panel of 3,027 cities, which comprise the sample for this paper. Within this sample, the median 1920 city population is 4,346; the 95th percentile is 48,414. Of these 3,027 cities, 415 are identified in our cutover data, and 384 with exact or approximate cutover timing.

B.3 Additional (supplementary) data

We also collect data from two additional AT&T archival sources.

AT&T data on dial diffusion, 1913-1972

Archival documents at the AT&T corporate archives include a two-page report providing the annual time series of the total number of Bell system telephones from 1913 to 1972, and a breakdown by the type of central office, manual versus dial (see "Bell System Distributions of Company Telephones," AT&T Archives and History Center, box 085-04-03-02). Using these data we measure aggregate dial diffusion within the Bell system (shown in Figure 1).

AT&T subscribers in large cities, 1915-1940

In addition to the AT&T dial diffusion data, we also collect data on annual local *telephone* adoption U.S. cities with over 50,000 population. The AT&T publication "Bell Telephones in Principal Cities" (AT&T 1915) was published annually, and made available to us by the AT&T Archives and History Center for years 1915 to 1940. Each volume of this publication reports the number of Bell system telephone stations in each city, as well as an estimate of the service area population (for measuring telephone penetration), and a breakdown of the percent of telephones which are business subscribers (vs. residence). We use these data to study how cutovers were related to, and subsequently affected, AT&T network growth.

C Supplementary Descriptives

Table C.1: Bell System telephones in major cities, 1915-1940

	All cities (mean)					
	1915	1919	1925	1930	1935	1940
Service area (1000s)	231.44	235.77	252.68	263.29	264.03	237.31
Telephones (1000s)	24.83	29.62	45.77	56.87	48.97	53.17
Fraction Business	38%	37%	37%	34%	36%	37%
Fraction Residential	59%	62%	61%	63%	61%	63%
Telephones per 100 pop.	10.09	11.65	16.72	20.04	17.06	20.44
Business	3.63	4.05	5.96	6.79	6.02	7.51
Residential	6.24	7.41	10.37	12.66	10.45	12.93
Observations	115	131	140	156	160	182
	Balanced panel (mean)					
	1915	1919	1925	1930	1935	1940
Service area (1000s)	239.21	269.13	305.56	342.24	350.12	338.09
Telephones (1000s)	26.20	34.80	55.98	74.72	65.53	77.18
Fraction Business	37%	36%	37%	34%	36%	38%
Fraction Residential	60%	62%	61%	62%	61%	62%
Telephones per 100 pop.	10.53	12.22	17.06	20.14	17.25	20.88
Business	3.78	4.26	6.19	6.99	6.19	7.95
Residential	6.54	7.76	10.43	12.51	10.39	12.93
Observations	105	105	105	105	105	105

Notes: Table reports data on the Bell telephone network from AT&T (1915), which covered markets whose service area contained $\geq$50,000 people. Mean values across sample cities for each of the statistics listed are shown by year. Note that the volume for 1920 was not available.

Table C.2: Bell System telephones in major cities, 1915-1940

	All cities (min-max)											
	1915		1919		1925		1930		1935		1940	
	p10	p90	p10	p90	p10	p90	p10	p90	p10	p90	p10	p90
Service area (1000s)	54.20	2482.00	53.40	2730.00	53.80	2967.00	51.40	3320.00	53.40	3270.00	52.40	3520.00
Telephones (1000s)	0.38	382.13	1.35	504.43	1.33	741.88	1.61	987.89	0.97	824.29	5.28	997.17
Fraction Business	19%	84%	22%	61%	13%	72%	19%	63%	19%	62%	16%	67%
Fraction Residential	9%	81%	30%	77%	25%	85%	29%	78%	22%	77%	33%	84%
Telephones per 100 pop.	0.51	22.52	1.16	24.77	1.36	39.26	1.41	40.12	0.88	35.80	9.39	41.51
Business	0.43	8.94	0.67	10.49	0.88	23.48	0.81	23.71	0.49	18.41	2.70	19.41
Residential	0.05	14.86	0.41	16.79	0.40	23.19	0.40	26.37	0.20	24.24	4.29	27.09
Observations	115	115	131	131	140	140	156	156	160	160	182	182

	Balanced panel (min-max)											
	1915		1919		1925		1930		1935		1940	
	p10	p90	p10	p90	p10	p90	p10	p90	p10	p90	p10	p90
Service area (1000s)	54.20	2482.00	58.60	2730.00	56.60	2967.00	73.10	3320.00	70.30	3270.00	70.30	3520.00
Telephones (1000s)	2.80	382.13	1.80	504.43	1.33	741.88	8.96	987.89	8.04	824.29	10.88	997.17
Fraction Business	19%	62%	22%	61%	22%	72%	24%	59%	25%	62%	27%	63%
Fraction Residential	23%	81%	30%	77%	25%	72%	36%	73%	33%	71%	37%	73%
Telephones per 100 pop.	3.87	22.52	2.58	24.77	1.68	39.26	10.54	40.12	9.98	35.80	12.01	41.51
Business	1.53	8.94	1.57	10.49	1.21	23.48	3.60	23.71	3.01	18.41	4.00	19.41
Residential	0.98	14.86	0.98	16.79	0.42	18.50	5.61	18.37	5.61	18.90	5.59	22.62
Observations	105	105	105	105	105	105	105	105	105	105	105	105

Notes: Table reports data on the Bell telephone network from AT&T (1915), which covered markets whose service area contained 50,000 or more people. Minimum and maximum values across sample cities for each of the statistics listed are shown by year. Note that the volume for 1920 was not available.

D Supplementary Results

D.1 Operator employment prior to automation

Interestingly, Table 3 does not indicate a statistically significant relationship between cutovers and young women's employment in telephone operation, which implicitly measures how much of this labor pool AT&T employed. Below we take an event study approach to evaluating this relationship, which the panel variation supports.[8] We focus on cities with ≤100,000 people in 1920, which were typically cut over to dial at once (Feigenbaum and Gross 2021). Using a decadal city panel, we estimate changes in the fraction of young women working in the telephone industry and in other industries prior to a city's first dial cutover, with the following specification:

$$\mathrm{Y}_{it} = \sum_{s} \beta_s D_{it}^{s} + \alpha_i + \delta_t + X_{it}\phi + \varepsilon_{it} \tag{D.1}$$

Here it indexes city i in year t, D_{it}^{s} are event study dummies (s indexing event time), α_i and δ_t and city and year fixed effects, and X_{it} are population controls. Our sample spans 1910 to 1940, and includes cities without a cutover as a control group, with identification coming off of the timing of cutovers in between. We cluster standard errors by city. Because these outcomes are only measured in the census at decadal frequency, we measure event time in ten-year intervals, and since our focus is explaining automation, we present only pre-event estimates below.

Table D.1, Panel (A) shows that young women's employment in telephone operation was growing rapidly in the run-up to cutovers, up 0.7 p.p. in the decade just before mechanization on an average base of 3.35 p.p. of group employment, a 20% increase in telephone operation's employment share. These changes were specifically driven by operators in the telephone industry: changes in the share of young women who were operators at *private* switchboards or worked in other occupations are not statistically different from zero, and the magnitudes are small relative to base levels. This suggests that labor market tightness in the broad sense did not drive automation; rather, AT&T's own growing demand for operators did. For comparison, in Panel (B) we run the same regressions for older women (age 46+). Older operators typically worked long-distance switchboards, which were not mechanized until after 1940. Here we find no such patterns.

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[8] We can do the same for population growth, but not unionization, as operator unions fizzled with the emergence of a company union in the 1920s. Event studies on population are consistent with Table 3.

Table D.1: Patterns of employment for select subpopulations in run-up to automation

Panel (A): Young, white, American-born women (age 16-25)

	Pct. who are tel. operators	Pct. who are in tel. industry	Pct. who are operators in tel. industry	Pct. who are operators in oth. industry	Pct. with occupation
Years -20 to -10	0.336*	0.389*	0.308*	0.028	1.248
	(0.136)	(0.152)	(0.132)	(0.021)	(0.986)
Years -10 to 0	0.723**	0.860**	0.677**	0.046	1.858
	(0.181)	(0.202)	(0.171)	(0.034)	(1.186)
N	11645	11645	11645	11645	11656
R^2	0.60	0.62	0.60	0.44	0.83
Year FE	X	X	X	X	X
Controls	X	X	X	X	X
Pre-period mean	3.35	3.77	3.33	0.01	38.44
Pre-period s.d.	2.72	2.93	2.72	0.07	11.65

Panel (B): Older, white, American-born women (age 46+)

	Pct. who are tel. operators	Pct. who are in tel. industry	Pct. who are operators in tel. industry	Pct. who are operators in oth. industry	Pct. with occupation
Years -20 to -10	-0.011	-0.070	-0.019	0.008	0.949
	(0.037)	(0.042)	(0.031)	(0.014)	(0.569)
Years -10 to 0	0.017	-0.026	-0.003	0.020	0.804
	(0.053)	(0.059)	(0.043)	(0.026)	(0.598)
N	11618	11618	11618	11618	11652
R^2	0.49	0.47	0.46	0.46	0.70
Year FE	X	X	X	X	X
Controls	X	X	X	X	X
Pre-period mean	0.11	0.18	0.11	0.00	14.07
Pre-period s.d.	0.56	0.69	0.56	0.02	4.88

Notes: Table reports estimates from an event study regression of the given outcomes in the run-up to a city's first cutover to dial. All estimates are relative to the period ≥20 years pre-cutover, and mean values of the dependent variables from this period are shown in the table. The underlying sample spans 1900 to 1940 but is restricted to cities with population ≤100k in 1920. * and ** represent significance at the 0.05 and 0.01 levels, respectively. SEs clustered by city in parentheses.

D.2 Organizational adjustments

Some of the organizational changes we previously described as necessary to automation are also empirically testable. Recall that telephone operators performed a multitude of tasks, of which call switching was the most important, but still only one. The official 1917 Bell Telephone occupational classification (AT&T 1917) lists "example duties" of telephone operators to also include furnishing information to subscribers; doing directory work, rate quoting work, or trouble work; and sending telegrams. The new equipment likely also required new caretakers.

The census data present an opportunity to document changes in the telephone industry workforce around automation, bringing us closer to measuring this phenomenon. In Table D.2 we estimate changes in industry employment of workers which might complement versus be displaced by the new technology. Concretely, we estimate the following specification, which is a difference-in-difference analogue to the event study specification in Appendix D:

$$\mathrm{Y}_{it} = \beta \cdot \mathbb{1}(\text{Post-cutover}_{it}) + \alpha_i + \delta_t + X_{it}\phi + \varepsilon_{it} \tag{2}$$

where it indexes city i in year t, α_i and δ_t are city and year fixed effects, X_{it} are population controls accounting for differential trends in large and small cities, since population was closely related to mechanization, and standard errors are clustered by city.

Consistent with the results of Feigenbaum and Gross (2021), we see that cutovers resulted in a roughly 50% reduction in the telephone operating force. That this is only a partial downsizing is consistent with the fact that telephone companies still needed operators for some services. We see a relatively larger decline in young operators, as young women were more intensively employed in the core activity which was mechanized (local call switching). The table also reveals countervailing growth in female office clerks and male electrical engineers. As discussed in Section 3, these workers complemented the mechanical technology in distinct ways, with office clerks taking up some of the residual tasks left behind as the operating force was downsized, and the electrical engineers tending to the mechanical equipment. Because these jobs were a smaller fraction of employment, however, the net effect was a 30% reduction in the total industry workforce.

Table D.2: Effects of dial on changes in employment in the telephone industry (diff-in-diff)

	Ln(Fem. operators)			Ln(Female ...)	Ln(Male ...)			
	All	16-25	26+	clerks	electr. engs.	linemen	clerks	Ln(All workers)
Post-cutover	-0.495***	-0.566***	-0.348***	0.115***	0.097**	-0.046	0.053	-0.301***
	(0.041)	(0.047)	(0.043)	(0.042)	(0.043)	(0.045)	(0.040)	(0.034)
N	10792	10792	10792	10792	10792	10792	10792	10792
R^2	0.87	0.81	0.83	0.76	0.68	0.78	0.75	0.90

Notes: Table presents results from a DID regression estimating the effects of local dial adoption on the (log) number of persons working in select occupations in the telephone industry. * and ** represent significance at the 0.05 and 0.01 levels, respectively. SEs clustered by city in parentheses.

As we have seen, many other adjustments were in fact made to accommodate automatic switching, even if most are not empirically observable. With perfect data, we might also want to measure the adoption of complementary technology for interconnection, new business practices such as revisions in cost accounting, local exchanges' management of transitional labor, or changes in system design like multiplexing (to accommodate higher traffic) or redundancy (as insurance against technology failure). And these are only a fraction of the organizational adjustments we documented in Section 3, each of which presents opportunities for further study.