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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 invented in the 1880s. We study what drove AT&T to do so, and why it took nearly a century. Interdependencies between call switching and nearly every other activity in AT&T's business presented obstacles to change: telephone operators were the fulcrum of a complex production system which had developed around them, and automation only began after the firm and new technology were adapted to work together. Even then, automatic switching was only profitable in larger markets—hence diffusion expanded when the technology improved or service areas grew. The example suggests even narrowly-defined tasks can be difficult to automate if they interact with many others.

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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. Forty years prior, amidst ongoing mechanization and concerns of technological unemployment, Congressional hearings had raised the spectre that "in a few years, [telephone] service will be thoroughly and completely mechanized" (Sullivan 1940). The completion of the all-dial system occurred nearly 60 years after the Chesapeake & Potomac Telephone Co. installed AT&T's first dial telephones in Norfolk, Virginia (November 1919), and 90 years after mechanical switching was invented (March 1889).

Today, anticipation of an imminent, sweeping wave of automation is high (e.g., Brynjolfsson and McAfee 2014, Autor 2015), in part due to the technological potential of robots and artificial intelligence (AI). Despite early enthusiasm, their impacts thus far have been limited: as Agrawal et al. (2022) observe, a decade into this AI wave, it has not yet had any such sweeping effect. Where it has been deployed, AI is largely being used in narrow applications, like product recommendations, that incrementally enhance existing products and services rather than fully upending the economy (Bresnahan 2021). This raises the question: what is taking so long?

In this paper, we explore reasons why automation can take a long time to have its full effect—and why, in this case, it took AT&T nearly a century. Our analysis will combine narrative and empirical evidence, and organizational and economic explanations, but first requires context. From the 1880s to 1980s, AT&T was the dominant U.S. telephone service provider, administering this service via a network of subsidiary regional operating companies. Telephone systems were initially designed to have operators physically connecting calls—a task known as "call switching"—putting them at the center of both the telephone network and AT&T's production system. Manual switching, in turn, shaped choices and activities across the business, including service offerings, plant and equipment, operations, prices, accounting, billing, customer relations, and more.

Though manual switching served early telephone networks well, expansion revealed its limits, as its complexity rose quickly in large markets with billions of possible connections, and switchboards became system bottlenecks. As AT&T grew, its service quality thus fell, and operator requirements exploded: by the 1920s AT&T was the largest U.S. employer, with operators over half its workforce. Company records show the limits of manual switching were known as early as the 1900s, when automatic technology was already being tested—yet it took AT&T several more decades to adopt it widely. We show in this paper that automation was hindered by interdependencies between call switching and the rest of AT&T's business: for automation to be productive required that the technology and business fit together. In practice, this required significant complementary innovation and adaptation across the firm, which were only resolved over time.

The example indicates automation can be challenged by interdependencies in organizations and production systems, because changes to any one task implicate others with which it interacts. We spend much of this paper examining this idea, and integrating task-based views of automation with a long literature which has studied interdependence in organizations (e.g., see Puranam and Raveendran 2013 for a review). We argue that the more interconnected a task is in its production environment, the more difficult its automation is thus likely to be. At the extreme, one task may interact with all others—a canonical case we label "integral tasks", adopting the language of prior research on interdependence in product and organizational architectures (e.g., Ulrich 1995), and formally model.[1] Consistent with the view that call switching approaches this limiting case, qualitative evidence reveals that AT&T made a wide range of specific changes to its business when it mechanized telephone operation. Econometric evidence provides a window into several of these changes, especially with respect to the composition of its workforce.

The challenge of substituting machines for workers in highly interdependent tasks thus (seemingly) contributed to AT&T's early delays in adopting mechanical switching. But once it recognized the necessary technical and organizational and adjustments, why did it take several more decades for mechanical switching to diffuse throughout the telephone network? The Great Depression and World War II caused slowdowns, but were too short-lived to explain this lag. The evidence instead suggests the economics of the problem do. Automation, like other technology, tends to diffuse first to large units with the scale to spread fixed costs, profiting on marginal cost savings. In this case, however, AT&T's goal was not shifting marginal costs down, but rather limiting the rate at which they grew, by reducing the complexity of serving large markets. The benefits of the technology in turn decayed very quickly in small markets. Because much of the population lived in rural areas served by small telephone exchanges, long lags may have been inevitable. Diffusion thus progressed as the technology continued to improve, and as local markets grew.

Through this episode, we provide a lens into some of the reasons why non-manufacturing firms automate production, and what might stand in their way. The historical U.S. telephone industry seems to be a straightforward setting for automation: AT&T had enormous scale, sophisticated

[1] The language used to describe organizational interdependence varies somewhat across this literature. Simon (1962), for example, compares "complex" vs. "decomposable" systems. Ulrich (1995) discusses "integrality" and "modularity", which is the subject of considerable later work; within this thread, Baldwin and Clark (2000) have been particularly influential. Other have also studied limiting cases of interdependency: Siggelkow (2002) describes firms' "core elements", and scholars from Rivkin and Siggelkow (2007) to (most recently) Karim et al. (2023) have studied "centralized" task structures where one task interacts with many others. Our choice of terms, and eschewing of the language of centralization, is meant to semantically distinguish features of organizational architectures from decision authority, which is a distinct phenomenon that can also be centralized.

management, extensive knowledge of automatic switching, access to capital, and it manufactured its own equipment, which it could tailor to its needs and precluded any contractual holdups. These features of the firm make it an attractive laboratory, because we can rule these factors out—and yet what remains is nevertheless a century-long adoption problem.

Our findings are consistent with research on complementarity and strategic fit, which has argued that interdependencies in complex activity systems can make isolated changes unprofitable, because they throw these systems out of alignment (e.g., Milgrom and Roberts 1990, 1995, Henderson and Clark 1990). Mechanical call switching seems to fit this description. Following similar logic, previous work has shown that technologies that create value through complementarities, like information technology (IT), have historically been slow to diffuse because they required additional technological or organizational innovation to achieve their full impact (e.g., David 1990, Bresnahan and Trajtenberg 1995, Bresnahan et al. 2002). We show that similar dynamics can arise with automation. In doing so, we connect task-based views of automation—which have grown increasingly prominent in economics and other fields, but which typically treat production systems as aggregations of independent tasks—to research on interdependence in organizations.

AT&T is nevertheless a specific case, raising the question of how general its example is likely to be. Perhaps what makes it most distinctive is its position as a regulated monopoly for most of the twentieth century, including the period we study. Rate of return regulation, through which regulatory bodies set telephone rates which limited AT&T's return on capital, in principle could have depressed incentives for cost-saving innovation. In practice, however it incentivized capital investments like mechanical switching, which AT&T could use to justify rate increases—and regulatory arbitrage (across federal and state regulators) created opportunities to profit from the difference (Mueller 1997). Moreover, if margins were fixed, AT&T's only way to grow profits would then be volume, in which case controlling costs was more attractive than raising prices—which in turn required clearing the bottleneck at the switchboard. Monopoly, meanwhile, conferred it with greater scale, facilitating technology adoption (Macher et al. 2021). Given these incentives, AT&T's 90-year mechanization seemingly requires other explanations, such as (though not necessarily limited to) organizational and economic factors we emphasize in this paper.

Throughout the paper, we discuss myriad settings where automation is challenged by interdependencies and integral tasks. Many candidate applications for AI have this flavor, as Agrawal et al. (2022) explain—but AI is only the tip of this iceberg. For example, when the U.S. Internal Revenue Service replaced manual labor in tax return processing with automatic data processing, it required a "total systems approach" to adoption, with a wide array of changes across the agency (BLS 1964).

We reflect on similar stories for retail barcode scanning (Basker 2012), ATMs in consumer banking (Bessen 2015), and more. Organizationally-challenging tasks for automation across these cases are recognizable as points in an activity system where production bottlenecks developed. We consider this a useful heuristic for identifying such tasks in other settings.

We proceed as follows. Section 1 provides a conceptual foundation for the paper. Section 2 reviews the history of AT&T, the U.S. telephone industry, and the development of mechanical switching. Section 3 discusses AT&T's reasons for and obstacles to automating telephone operation, emphasizing organizational factors, and Section 4 gives these ideas structure with a simple model. Section 5 presents evidence of organizational changes accompanying mechanical switching in local markets. In Section 6 we suggest an explanation for the long residual lags in diffusion once automation began. Section 7 discusses the generality of this example and concludes.

1 Conceptual Foundations

Since Griliches (1957) and Rogers (1962), scholars in management, economics, and sociology have studied obstacles to technology adoption, with reasons ranging from fixed costs and indivisibility to financial frictions, information, uncertain returns, and more.

Complementarities have had an increasingly prominent role in modern diffusion studies, especially of information technology and general-purpose technologies (GPTs). Motivated in part by the productivity paradox of the late twentieth century, David (1990), Bresnahan and Trajtenberg (1995), and others have argued that because GPTs create value via complementarities, they may be slow to register their full impact until additional technological or organizational changes come into place. These investments not only take time, but may also be slowed if complementary innovators do not internalize the impact of their efforts on joint value creation.

Contemporary and subsequent research has studied this problem within the firm. A now widely-accepted view is that supermodularity may limit individual technologies' impact on firm performance, or even make them counterproductive, thus slowing their spread. The reason, as Milgrom and Roberts (1990) and others (e.g., Henderson and Clark 1990, Siggelkow 2001) have argued, is that firms' assets, choices, and activities can be thrown out of alignment by isolated changes—such as when a firm adopts new production methods without wider changes to its production system. As a result, this work shows, changes that seem value-enhancing can be value-destroying unless additional investments are made to preserve internal alignment.

The logic of complementarity has been the basis for a broad set of research on technology diffusion. Bresnahan et al. (2002), for example, show that firms' productive use of IT involves investments in both tangible and intangible capital, including changes in organization. Brynjolfsson et al. (2021a) have similarly shown that the impact of modern predictive analytics on firm performance depends on complementary assets and practices like production strategy, IT investment, and an educated workforce. Brynjolfsson et al. (2021b) summarize this literature's answer to the Solow Paradox by showing that the necessity of intangible investments can delay the measured productivity impacts of GPT-like technologies but lead to a take-off in later years.

The idea that system-level change is necessary for major technologies to have wide-felt impacts is now practically canon. Despite this, not all technologies—and not even all historically impactful technologies—have been accompanied by such systemic change. Hybrid seed corn did not require dramatic changes in farming practices and was adopted quickly when suitable to local conditions (Griliches 1957). Vaccines and antibiotics diffused rapidly in the mid-twentieth century, with large impacts on public health but no significant changes in medical practice. Even among technologies thought to be GPTs, specific applications need not involve major changes in the organization of production. Agrawal et al. (2022), for example, draw a distinction between applications of AI which can frictionlessly slot into existing tasks and structures ("point solutions"; e.g., fraud detection in financial transactions) versus those that require the design of entirely new systems to be productive ("system solutions"; e.g., ship-then-shop for online retail).

Implications for automation

This paper brings these ideas into focus as they relate to automation. Our first observation is that like AI, automation technologies can take different forms in different contexts. In many cases they require no further investment. In others, they may require many complementary changes. One goal of this paper is to understand why. To motivate this analysis, it is useful to first articulate what makes automation distinct from other kinds of technological change. Whereas previous examples, like IT, represent technology bundles that often support entirely new production systems in which some previous tasks are rendered obsolete, automation does not obsolesce tasks, but rather has the specific, narrower effect of replacing manual labor in them.

Given this narrower scope, that automation can sometimes have similarly systemic implications is perhaps surprising. In making sense of this puzzle, we find it helpful to consider a task-based view of production. In task-based economic frameworks, production consists of individual tasks, which can be performed by people or by machines, and which aggregate into final goods (e.g., Acemoglu and Restrepo 2018). In practice, when work is organized, these tasks may be bundled up into sets, which have in various work in economics, strategy, and organizational theory been described as activities (our preferred nomenclature for this paper), modules, clusters, production steps, or simply jobs, and which are typically the work of a single organizational unit—or in some cases, even a single worker. A large literature in organizational design has explored the implications of interdependencies for the way organizations are structured, to which we will return below. For now, we note that economic models typically treat tasks as independent, abstracting from the linkages that are often present within production problems. As a result, the finer details of how automation affects firm strategy can be obscured in traditional frameworks.

From this perspective, we observe a dichotomy paralleling Agrawal et al. (2022). Some automation reduces to a simple technology adoption problem. This is the case when machines substitute for labor in simple, discrete tasks that are performed independently of others—for example, automatic washers and dryers replacing laundering a century ago, or grocery store robots that scan shelves for stock-outs today. In other cases, machines may substitute for labor in jobs with many tasks, and/or tasks that interact with many others. Robotic restaurant servers must not only serve food, but also take orders, clear tables, and bring the bill, in sync with other restaurant activities (i.e., when food is cooked, or customers are finished eating)—or else systems must be reconfigured to do these tasks by other means. As another example, when barcode scanning was adopted in retail in the 1970s, it substituted for labor in store management and customer checkout, but to realize its full benefits, stores needed not only scanners but also IT systems, inventory management software, complementary supplier investments in packaging and labeling, employee training, customer education and more (Basker 2012, Basker and Simcoe 2021).

Recognizing this difference, we emphasize a distinction between two types of automation problems: one where technology substitutes for labor in independent tasks and is simple to deploy with few other changes, and others where technology substitutes for labor in tasks (even a single task) that interact with many others, and may thus require changes across entire task systems. The interdependencies we emphasize are widely studied by organizational design scholars, often in examining what organizational structures improve firm performance, given interdependence in the task set. Here we more or less take the structure of the firm as given, and instead study how interdependence affects the choice of technology in individual tasks, at times focusing on the limiting case: when a single task interacts with all others. A key feature of this problem is that firms benefit from congruence in production technology across tasks which interact, and the value of congruence may constrain investment choices, as we will see in Section 4.

This focus on interdependent tasks connects the modern manufacturing paradigm to task-based production, and brings clarity to when and why automation may be a straightforward vs. complex organizational problem. It also suggests a reason why automation may take time to percolate into firms and across the economy. Moreover, it allows for the possibility that technology be adapted to the firm, keeping existing interdependencies in place—not just the firm to the technology. As we will show, AT&T's technology and business developed jointly.

Connections to organizational design

Our work is thus closely related to the extensive literature on interdependence in organizational design (see Puranam and Raveendran 2013, Raveendran et al. 2020 for reviews)—which builds on a view of organizations as complex systems (March and Simon 1958, Simon 1962) and a documented, well-defined set of canonical interdependency patterns (Thompson 1967). These early observations have since been found to have several implications. One is the potential impact of modularization—the division of firms' task systems into more loosely federated subsystems—in reducing the costs of complexity (e.g., Baldwin and Clark 2000, Ethiraj and Levinthal 2004, Rivkin and Siggelkow 2003, 2007, Zhou 2013).[2] A second is the potential importance of aligning product and firm architectures (e.g., Sanchez and Mahoney 1996; also see Langlois 2002). A third is that internal dependencies can create obstacles to organizational change, including organizational adaptation to environmental change (e.g., Hannan and Freeman 1984, Levinthal 1997).

Technological change is one of many varieties of environmental change which can not only impact organizational design (Barley 1986, Cohen 2013), but whose effects on firms are also moderated by organizational design. Our focus in this paper—automation—is an increasingly important strain of technological change, and different from prior examples in this literature in two essential ways. First, whereas many technologies are implemented at the system level (e.g., enterprise software), automation targets individual tasks. Second, it explicitly replaces workers in these tasks. As a result, automation will not necessarily have system-wide consequences: its impacts will generally only ripple across the connected set of tasks, which can be as small as a singleton. This, together with the fact that automation substitutes for workers, suggests that when automation technology is adopted in fully-confined settings, firms can leave existing organizational structures and routines intact. Conversely, any systemic implications of automation are attributable not to the technology, but rather to interdependence around an automated task.

Thus, although automation is often only intended for narrow components of a production system, even these (seemingly) isolated substitutions can have systemic effects. This observation points us to a technology-task nexus where we think there is room for further refinement in the organizational

[2] A corollary literature has also cautioned of bottlenecks at tasks which connect many others, such as those connecting otherwise-independent subsystems (e.g., Baldwin 2018, Karim et al. 2023). There the emphasis is on choke points in production, more so than obstacles to change (the focus of this paper)—though these may often coincide, and telephone call switching seems to us to be an example of both.

design literature in studying (i) firms' choices over production technology in individual tasks—especially the choice between manual or machine methods—and (ii) organizational structures that are compatible with different production technologies.[3] Pointing out this gap, and providing some initial analytical framing, is one intended conceptual contribution. The other is to bring ideas from the extant literature in organizational design into the economics of automation, bridging two bodies of work which have thus far only been loosely connected.

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" telephone companies which built competing networks in cities and entered markets (especially rural areas) where AT&T had not. Thereafter, AT&T focused on consolidating 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 each other. 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 equipment was designed to be manually operated. As its business developed into a cross-country network serving millions of users, it did so on the presumption that operators would be connecting calls.

[3] A third opportunity is to more deeply examine how firms' organizational structures (e.g., job boundaries) change with automation (building on Barley 1986, Hasan et al. 2015, and others).

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 pace at which AT&T expanded is astonishing: in 1891, its scope was limited to the northeast U.S., but by 1909 it had exchanges throughout the U.S., with its densest coverage across the eastern half of the country.

AT&T's regional operating companies owned and managed this network, providing service in their respective territories (Appendix Figure A.2).[4] They provided two main types of service (local and long-distance) to three main categories of users (business, residential, and payphone). Customers leased their line and their telephone sets from the telephone company, and were typically charged per minute for calls, with rates varying by location, customer type, and service. Telephone companies also offered other services, such as information service and emergency service (i.e., 911). They also supported private branch exchange (PBX) service, in which business customers could install an internal switchboard where an on-site operator would route calls to/from extensions to individual telephone sets within the organization. All equipment used in the Bell system, whether on the exchange side or customer side, was made by Western Electric.

Reflecting its scope and scale, AT&T's labor needs were significant—and overwhelming concentrated in operators. For example, of the nearly 215,000 individuals in the 1920 census working in the telephone industry with a known occupation, 65% were telephone operators; 11% were bookkeepers, secretaries, and other clerical workers; 10% were linemen, servicemen, and other laborers; and 4% were electricians and electrical engineers. As the network grew, so did its workforce: by 1930, there were nearly 190,000 telephone operators in the telephone industry, the vast majority of whom were young women (Feigenbaum and Gross 2022).

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

[4] Though these firms were geographically exclusive and independently managed, they interconnected and shared the same owner, business model, technology, and organizational structure.

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).

Telephone exchanges had several categories of operators. As Erickson (1947) explains, an "A" board operator would look for pilot lights indicating a waiting caller and take instructions. If the destination was local and she was working a "dual" switchboard, she could connect the call directly, but in most cases, 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 connect to the destination exchange. Operating rooms also had "long-distance" operators, who specialized in building long-distance connections; "information" operators, who could help customers look up telephone numbers by name or 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, it is clear that operating the telephone network was a complex activity requiring significant division of labor and coordination among the operators doing the yeoman's work of call switching—the essential task. Keeping this system synchronized was its own challenge. 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 mechanical 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

[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 (Chapuis 1982).

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 by the Strowger Automatic Telephone Exchange Company, which became the Automatic Electric Company, an analogue to 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. Pilot tests with automatic equipment developed in the early 1900s were unsuccessful: these systems "did not permit any material savings or better service than manual," and it was concluded that "the dial telephone art was not sufficiently advanced to justify the use of such equipment" (Freeman 1937).

As Freeman (1937) explains, part of the challenge was that manual switching "had been developed to a point where it was giving fast, accurate, and dependable service in practically all sizes of exchange areas." Research into mechanical switching at AT&T nevertheless continued: "from 1907 on, the automatic system was the subject of almost continuous laboratory test, field studies, and economic comparisons" (Freeman 1937). It would be another decade until mechanical switching could match manual operation on connection times and error rates, and internal estimates suggested it may generate savings in large cities. In 1917, AT&T began advising that its subsidiaries adopt mechanical switching for local service in large, multi-exchange cities, backing this recommendation with evaluations of relative connection speeds, accuracy, cost, versatility, customer sentiment, and the severity of the "labor problem" (Gherardi 1917). The engineering department anticipated that mechanization would reduce operator requirements by 70-80%.

At first view, it might seem as though mechanical switching was mainly a technological problem. But AT&T documents also make clear that transitioning from the manual to mechanical system required a substantial amount of organizational learning—through a mix of field trials, learning by observation (of independents), and learning by acquisition.[6] Learning by doing was likely the most impactful, and continued into the dial era as it refined its approach to mechanical switching, which allowed later exchanges to start off further down the learning curve.

Table 1 summarizes the growth of the telephone industry from 1902 to 1937, using data from the quinquennial Census of Electrical Industries. Over the period, the industry grew nearly 20x in

[6] For example, AT&T's internal history of the development of mechanical 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 ... "Experience was [also] obtained with a number of independent plants of the step-by-step type which were acquired" (Freeman 1937).

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.

[Table 1 and Figure 1 about here]

3 AT&T's Drivers and Barriers to Automation

AT&T archival records allege several reasons for automating call switching. Freeman (1937) writes that in the late 1910s, the firm faced three pressures: the complexity of rendering manual service, a constrained supply of operators, and rising operator wages. At a 1916 Bell System Technical Conference, an AT&T engineer likewise noted the technical limits to manual operation and emphasized the "necessity of proceeding with a machine switching program [so] that the service requirements of the future could be adequately cared for" (Freeman 1937).

AT&T's main problem was that manual switching had large diseconomies of scale. Because the number of connections in a telephone network is quadratic in users, manual operation was especially complex in large markets. This challenged the ability of manual systems to make fast and accurate connections, and necessitated more and better operators—who needed to reach more switchboard positions, learn more exchange names, and be able to connect calls through more trunking (Freeman 1937). Although rate of return regulation implied that AT&T could request increased rates on the grounds of its rising costs, this was at best a stopgap (since costs would keep rising), and politically difficult for regulators often accused of being too permissive with rate increases instead of pressing for efficient operation (Mueller 1997). It was also imperfect for AT&T, since raising prices would curb demand, limit growth, and constrain shareholder value.

A closely-related issue was a shortage of qualified operators (Gherardi 1917). Even with constant marginal costs, AT&T's growth brought into question whether there were enough workers to meet its operating needs—and at what price. Diseconomies of scale compounded this problem, since as the telephone network grew, its operator demand grew even faster. AT&T would have eventually had to employ essentially all of the young women in American cities as operators in order to supply universal telephone service: Orbach (1930) explained that "If [AT&T's] present rate of growth continues, in a few years we will need most of [this population]."[7] Compounding this problem was

[7] 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 demographic and behavioral criteria. The set of eligible workers was thus narrow—though AT&T would have faced the same challenges even if its hiring pool were broader.

that operator wages were being driven higher, allegedly by labor market competition—though in our empirical analysis we will not find evidence that mechanization relates to levels or trends in local employment rates (a proxy for labor market tightness).

3.1 Organizational barriers

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. Despite its limitations, however, AT&T was relatively bound to manual operation. From the beginning of the telephone era, telephone service had been designed around operators. 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) illustrates an activity map of the various activities 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]

Figure 3 depicts interdependence across AT&T's business, but illustrates that call switching is the most interconnected component of the system. Call switching's centrality in this web of activities makes it our canonical example of an "integral task". Its embeddedness meant that significant changes in call switching technology (like automation) were not a straightforward proposition, as they would have ripple effects across the business, and risked destroying value unless the technology and this system could be (re-)designed to work together. Some of this redesign was technological: Lipartito (1994a) explains that "Strowger switches required a number of improvements before they could be used ... several other technical refinements were needed to integrate manual and machine switching methods," including semi-mechanical switchboards that could interface between them. Others lived at the business or system level. AT&T also needed to prepare contingencies for user or mechanical error, and to convince operating companies' managers to adopt mechanical switching, overcoming their skepticism on reliability and cost savings.

These obstacles were overcome by dozens of innovations which were gradually discovered, including changes in both switching technology and in AT&T's business. Figure 3, Panel (B) lists examples. 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. At the corporate level, AT&T invested decades, and significant capital, in improving automatic switching equipment until it was competitive in cost and performance. It also needed to produce fully-vetted recommendations and protocols for adoption, and educate operating company managers on the new technology. Within its Western Electric subsidiary, it then 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. 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 installation, leading to a sequence of government reports and eventually Congressional hearings pitting AT&T executives against operator union representatives.

3.2 Evaluating other interpretations

Complementarities are by definition two-directional: that call switching technology complemented (for example) billing practices, or telephone handset design, also implies they complemented call switching. What evidence is there that call switching was the bottleneck in this system, and the focus of AT&T's change—versus these complementary activities? Put differently: did AT&T adopt mechanical switching to support changes in other parts of the business? Two pieces of evidence reinforce our interpretation of call switching as the specific task whose technology AT&T sought to change: (i) historical accounts and analysis identifying switchboards as bottlenecks (e.g., Lipartito 1994a,b), and (ii) voluminous company records documenting AT&T's efforts to improve mechanical call switching technology and incorporate it into its business—in which these complementary changes are noted in passing, but not the primary focus of discussion.

An alternative interpretation, however, is that the obstacle to automating call switching was not its interaction with activities across AT&T's business, but rather that it was bundled into one job with other tasks which (some) operators also performed, like monitoring calls and writing billing tickets—and these were difficult to disentangle. But these tasks were not so tightly tied up that they could not be separated; indeed, with mechanization, these tasks were parceled out to other workers. As we described above, the crucial sources of interdependence seem to have been between call switching and other parts of the business.

3.3 Discussion

AT&T's example highlights the challenges of automating interdependent tasks. The number of ways in which the firm needed to be adapted to automatic technology (or vice versa) is among the reasons why it took decades for AT&T to use it.[8] With experience, AT&T eventually developed a repeatable template for local adoption, which was described in contemporary newspaper articles: installation of central office equipment, distribution of dial handsets and directories, user training, transitional labor, and eventually, physically connecting wires to the mechanical equipment, after which subscribers would begin using their dial telephones.

4 A Model of Interdependence

To provide a more structured understanding to how interdependence interferes with automation, we present a model of task-based production. Here we focus on a limiting case of interdependence, which broadly matches the AT&T setting and articulates the holdup that even a single task can create for automation due to its complementarities with others. This model features a monopolist firm engaged in production requiring several activities, with activity-specific tasks and one common task.[9] Supporting analysis and proofs are provided in Appendix B.

We begin with a few building blocks. Consider a monopolist firm which sells to a market of size M with linear demand $Q(P) = M - aP$. The firm's profit function is $\pi = (P - c) \cdot Q(P) - FC$, where c and FC are marginal and fixed costs, which we give structure below.

This firm has a task-based production function. Each unit of output requires performing set of activities $i = 1, ..., n$, each with an associated task i. These could, for example, be the activities of independent departments that produce intermediate components that are later combined to make a final good (the simplest example, which we will continue to use); a physical, sequential production line in which a raw inputs are incrementally converted to output across successive stages; or a complex activity system like that shown in Figure 3.[10] We assume these activities are independent of each other but that in this production problem there is a distinct task, $i = 0$, which enters all activities, and which we label the *integral task*. Conceptually, in a component-based production system this might be final assembly. Alternatively, in a sequential production line, it might be a shared source of motive power. In this paper, it is telephone operation which interacts with most other production activities. Other examples can be readily imagined.

We assume output quality is fixed but prices, quantities, and production costs are endogenous, the latter as a function of the firm's technology choices. Each unit of output incurs a marginal cost c,

[8] Appendix Figure A.5 provides prima facie evidence of catalysts and obstacles to mechanical switching, drawing on newspaper reports. Several articles describe network growth and capacity constraints as the impetus for automation. Others describe the technical and business challenges of adopting mechanical switching.

[9] As in Section 1 we continue view activities as bundles of closely-related tasks within a firm (which might, e.g., have an associated functional department, like finance or marketing), though to reduce dimensionality of the model and convey the key intuition, we will model these activities as having one associated task.

[10] These examples map to Thompson (1967)'s pooled, sequential, and reciprocal interdependence.

which is an aggregation of the cost of activities $i = 1, ..., n$, each of which requires $g(i)$ to perform. We further assume that marginal costs are increasing in n (the total number of tasks), due to operational complexity, such that $c = \left(\sum_{i=1}^{n} g(i)\right) n$. Although this assumption is not required for our core results in this section, it will allow us to enrich the analysis.

Each activity i requires performing both task i and the integral task (e.g., producing a component, and attaching it to the assembly frame). We assume there exist two potential technologies for each task: manual and automated. We treat automation as a fixed cost investment that reduces marginal costs, assuming that the firm can adopt automation technology in each task at a cost θ and reduce its marginal cost in that task by $\frac{1}{2}\alpha$, where $\alpha > 0$. We will further assume there are benefits to using a common technology in complementary tasks (or, conversely, costs of incongruence when not), following the large literature on complementarity in organizations (Brynjolfsson and Milgrom 2013). To operationalize these assumptions, we define $g(i)$ as follows:

$$g(i) = 1 - \frac{1}{2}\alpha(\gamma_0 + \gamma_i) - \beta \mathbb{1}(\gamma_0 = \gamma_i)$$

where $\gamma_i \in \{0, 1\}$ indicates whether task i is automated, $\frac{1}{2}\alpha$ is the marginal cost reduction from automating each of the constituent tasks, and β is the additional benefit of using congruent technology in task i and the integral task. To ensure marginal costs $g(i)$ are positive when $\gamma_i = 1$ for all i (in which case $g(i) = 1 - \alpha - \beta$), we assume that $\alpha + \beta < 1$.

We seek to evaluate how automation affects profits, and how those effects vary in specific parameters of the model, including market size (M), the value of congruence (β), complexity (n), and ultimately the existence of the integral task itself. Because congruence is valuable ($\beta > 0$), the incentives for piecemeal changes to the firm's production technology may be low, as it will come at the expense of congruence. We examine the degree to which this is the case here.

To solve the firm's technology choice, we proceed in two steps:

1. Solve for equilibrium P^* and Q^* (and thus π^*), conditional on c
2. Solve for technology choices, taking $\pi^*(c)$ as given

Differentiating the profit function $\pi = (P - c) \cdot Q(P) - FC$ with respect to price and taking first order conditions, we obtain equilibrium prices and quantities $P^* = \frac{M+ac}{2a}$ and $Q^* = \frac{M-ac}{2}$ (see Appendix B). Equilibrium profits, in turn, are $\pi^* = \frac{(M-ac)^2}{4a} - FC$. At the time the firm chooses technology, it takes this downstream profit-maximization problem as given, and seeks to select the profit-maximizing technology bundle $\tilde{\gamma}_i = \{\gamma_i\}$. Recognizing that c and FC are endogenous to $\tilde{\gamma}_i$, we write equilibrium profits as $\pi^*(\tilde{\gamma}_i) = \frac{(M-ac(\tilde{\gamma}_i))^2}{4a} - FC(\tilde{\gamma}_i)$. We will proceed to evaluate the four scenarios below, spanning from zero to partial to complete automation.

Automation scenarios: None, partial, and complete

Scenario	Parameters			
	γ_0	$\{\gamma_i\}_{i=1}^n$	c	FC
1. No automation (baseline)	0	0	$(1-\beta)n^2$	0
2. Automation of production tasks	0	1	$(1-\frac{1}{2}\alpha)n^2$	$n\theta$
3. Automation of the integral task	1	0	$(1-\frac{1}{2}\alpha)n^2$	θ
4. Automation of all tasks	1	1	$(1-\alpha-\beta)n^2$	$(1+n)\theta$

We immediately see that automation of individual production tasks is dominated by automation of the integral task, because it produces the same marginal cost savings at lower investment level (intuitively: automating the one task that enters all production activities is more attractive than automating all activity-specific tasks).[11] We will thus restrict attention to scenarios (1), (3), and (4). As a regularity condition, we assume $M > \max\{a\left(1-\frac{1}{2}\alpha\right)n^2, a\left(1-\beta\right)n^2\}$, which ensures production can profitably occur in all automation conditions.

We first establish the returns to partial and complete (full) automation (i.e., automating the integral task or all tasks), by differencing equilibrium firm profits under each condition. These returns are established in Lemma (1) and denoted $\Delta\pi_p$ and $\Delta\pi_f$, respectively.

Lemma 1. *The returns to partial automation ($\Delta\pi_p$) and full automation ($\Delta\pi_f$) are:*

$$\Delta\pi_p = \frac{1}{4}n^2\left[\left(2M - an^2\left(2-\frac{1}{2}\alpha-\beta\right)\right)\left(\frac{1}{2}\alpha-\beta\right)\right]-\theta$$
$$\Delta\pi_f = \frac{1}{4}n^2\left[\left(2M - an^2\left(2-\alpha-2\beta\right)\right)\alpha\right]-\left(1+n\right)\theta$$

These expressions have several important characteristics, which are summarized by Proposition (1). These include straightforward dynamics: as fixed cost of automation (θ) falls or the marginal cost savings of automation (α) grows, so do the returns to automation. Larger markets (M) also increase the returns to automation (which will grow with scale).

Proposition 1. *Suppose $\frac{1}{2}\alpha > \beta$. The returns to partial automation are then increasing in M and α and decreasing in β and θ. The returns to full automation are increasing in M, α, and β, and decreasing in θ. The effects of increasing n (the cardinality of the production activity set) are positive for partial automation and ambiguous for full automation.*

Interestingly, the returns to automation can be increasing or decreasing in the scope of the activity system (n). Partial automation always has higher returns in larger activity systems, as the integral

[11] A fifth scenario not in the table is the automation of some, but not all, production tasks. This scenario is strictly dominated by either no automation (if $\beta > \frac{1}{2}\alpha$, i.e., congruence is more valuable than task-level cost savings), or automation of the integral task (vice versa). See Appendix B for explanation.

task enters more activities. With full automation, however, large activity systems present three competing forces in the comparative statics. On the one hand, scale (M) increases the returns to automation, as task-level cost savings scale up with quantity. On the other hand, larger activity systems require larger investments in the new technology (θ) across more tasks. Moreover, all else equal, adding tasks increases unit cost, which tempers the benefits of automation generally: at the limit, automation cannot overcome the cost of a many-step production process. This is especially the case when adding tasks increases production complexity.

One direct implication of Lemma (1), however, is that automation may not be a profitable investment in the first place. Two straightforward reasons can be that the market is too small to support the investment, or the technology is not sufficiently productive at a given cost. A third reason, however, is the value of congruence—i.e., that interacting tasks are performed by the same technology (manual or automated). When congruence is valuable relative to task-level cost savings of automation (particularly, when $\beta > \frac{1}{2}\alpha$), partial automation at the expense of this congruence will not be profitable. We establish this result in Proposition (2).

Proposition 2. *When $\beta > \frac{1}{2}\alpha$, partial automation is not an equilibrium outcome at any θ.*

Though partial automation may be ruled out by the high value of congruence, complete automation may still be a possibility, since it preserves this congruence. Complete automation, however, requires that the technology yield sufficient marginal cost savings to justify its fixed cost. Proposition (3) argues that if the technology is not sufficiently productive—in the sense that α is too low relative to θ—complete automation will not be profitable either.

Proposition 3. *When α is small relative to θ, full automation is not an equilibrium outcome.*

An added challenge of automating all tasks (versus the integral task) is its low productivity: for activity-specific tasks, an investment of θ creates savings of $\frac{1}{2}\alpha$ (vs. the $n \cdot \frac{1}{2}\alpha$ savings of automating the integral task). The minimum level of α for automating these activity-specific tasks, and in turn the complete system, is thus higher than for the integral task alone.

The implication of these results is that automation (of any/all tasks) may precluded by the combination of (i) low task-level savings from automatic technology, which discourages automation of the complete production system, and (ii) complementarity, in the form of value derived from using common technology across tasks, which discourages even partial automation of the integral task. In this case, there are two paths to automation: either market growth or innovation that improves the replacement technology's cost or performance characteristics—in this case, θ or α. Moreover, when such improvements arrive, changes across the entire production system are likely to follow, preserving congruence across interconnected tasks. To a first order, this pattern describes what we observe with AT&T: a manually-operated telephone network that struggled to replace operators until both automatic switching improved and it developed new approaches to other, interrelated firm activities that preserved complementarities across the system.

5 Evidence of a Changing Production System

Historical data can potentially provide insight into the degree to which mechanization involved changes to AT&T's production system. Though many of the adjustments we described in Section 3—such as price changes, building design, numbering systems, etc.—are difficult to systematically measure, one opportunity is to examine the structure of the telephone industry's workforce. As Atack et al. (2019) have shown, changing occupational structures can point to underlying changes in the set of firm activities and how these activities were carried out.

To evaluate changes in telephone industry employment, we combine two main sources of data: (i) city-level data measuring the date dial service was initiated, and (ii) individual-level census data from 1910 to 1940, which report occupation and industry. At the core of this exercise 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. We instead rely on a combination of historical newspaper reports and an AT&T administrative list of cutovers in large U.S. cities.

Our newspaper-based data collection exploits 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 sources 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 AT&T on the 164 U.S. cities with population >50,000 in 1937, which provide the date of each city's first Bell cutover, which we update to 1940 with additional manual research (AT&T 1937). In total, 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).[12] We then measure these cities'

[12] 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 C for complete details of the data collection effort.

earliest cutover. As we document in Appendix C, 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 IPUMS complete count U.S. census data for 1910 to 1940 (Ruggles et al. 2019), which provide individual-level information on the entire U.S. population, including geographic, demographic, and occupational characteristics. We first undertake an effort to harmonize city names in the census data (Appendix C), 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. We then filter to working-age adults (age 16-65) in cities who reported working in the telephone industry—which is generally going to be synonymous with an AT&T operating company, especially in cities. For each city-year, we measure the number of workers in the full range of industry occupations. 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.[13]

Figure 2 illustrates the variation in these data, mapping all cities with dial cutovers in our newspaper data through 1915, 1920, and so on up to 1940, with bubble sizes corresponding to the observed number of cutovers.[14] This variation will be instrumental to our empirical analysis, which we will identify off the panel. The implied fraction of the U.S. population exposed to mechanical switching in 1940 (i.e., living in a city with at least one cutover) is roughly 53%—the same order of magnitude as the 56% of Bell exchanges which were on dial at the end of 1939.

[Figure 2 about here]

Automation-driven changes in AT&T's workforce

Table 2 provides a descriptive view of the telephone industry workforce, listing the top 10 industry occupations in 1920 and their share of industry employment from 1910 to 1940. The table restricts to working age adults in cities and with a known occupation. More than half of telephone industry employees were operators, but it employed workers in a wide range of roles including telephone linemen, clerks, bookkeepers, electricians and engineers, inspectors, and managers. These categories are consistent with AT&T's internal occupational classification (Appendix Figure A.4), which identifies these titles among its occupational classes.

[13] 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.

[14] These data include independents' cutovers, as it is generally difficult to discern non-Bell cutovers in the data. As previously discussed, the vast majority of telephone service in this sample was provide by AT&T companies, and we have good reason to believe that after 1919, these are nearly all AT&T cutovers.

[Table 2 about here]

We relate changes in the local telephone industry workforce (which is effectively synonymous with the AT&T workforce, for the cities in our sample) to the adoption of mechanical switching with a difference-in-differences specification, exploiting the staggered adoption of mechanical switching and comparing outcomes before and after each city's first cutover. Our focus will be the sample of cities with population ≤100,000 in 1920, which were typically single-exchanges cities and were thus converted to dial all at once (whereas large cities were converted in a more piecemeal fashion—a pattern evidenced in Appendix Figure C.2). Of the cities in our initial sample, 2,846 meet this condition, of which 261 had a cutover prior to the 1940 census.[15]

Concretely, we estimate the following event-study specification:

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

where i and t index cities and census years; α_i and δ_t are fixed effects; and X_{it} are time-varying controls. Outcomes Y_{it} are an array of industry workforce characteristics, especially employment in specific occupations. Controls include state-year fixed effects and log city population crossed by year, which accounts for differential changes in larger and smaller markets and is important because market size is closely related to cutovers, as we find in Section 6. Though state-year fixed effects can account for regional trends, other forces may have been trending differentially at the same time as cutovers in different-size local markets. As an empirical matter, we find that this control can eliminate differential pre-trends across the outcomes we study.

Table 3 reports the effects of cutovers we estimate on log telephone industry employment in several occupations that might have ostensibly been affected by automation, including (primarily female) operators, clerks, and bookkeepers and (primarily male) electricians and electrical engineers, mechanics, and linemen. Consistent with Feigenbaum and Gross (2022), we find that cutovers resulted in a nearly 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 several functions, including long-distance, information and emergency service.

The table also indicates countervailing growth in occupations such as clerks and mechanics, who would have taken up residual tasks that operators had previously performed or new tasks that

[15] This sample also restricts to cities without a pre-1917 cutover, because our newspaper data collection was limited to articles published between 1917 and 1940, and our coverage of cutovers pre-1917 is therefore incomplete—although we do not consider this to be problematic, as pre-1917 cutovers were only performed by smaller, independent telephone companies (rather than AT&T), and the results are not sensitive to this choice.

the automatic equipment required. The most telling evidence that automation required a systemic solution may be in the declining employment of electricians and countervailing growth of electrical engineers, which can be interpreted as growing demand for workers who could not only install and service electrical equipment but also (or instead) implement new electrical and electromechanical systems, as mechanical switching required. Closer inspection of specific job titles reported by census respondents (as opposed to the occupational classes used in this analysis) reveals that this shifting demand is directly reflected in the distribution of job titles—for example, in the fraction of AT&T workers who reported an electrician versus engineering title.

[Table 3 about here]

In Table 4, Panel (A), we estimate separate effects on the log number of younger (16-25) and older (26+) operators (Columns 1 and 2), finding smaller effects for older operators, and accordingly show that the mean age of operators (Column 3), and the share that were in the older age group (Column 4), increased after cutovers. This compositional change is consistent with the view that remaining call switching tasks were more complex than the local service that was automated and required more skilled, mature, or experienced operators.

Panel (B) examines employment changes in managerial and quality control functions, both of which grew following the adoption of mechanical switching (albeit incrementally, and from an initially-low base; Columns 1 and 2). Coupled with an overall 30% decline in industry employment (led by the reduction in operators; Column 3), these changes imply a large decline in mean managerial span of control (Column 4). These changes appear to stem from the reduction in the operating force, an activity in which managerial effort had high returns to scale—since supervisory operators could oversee a complete row of junior operators, and chief operators managed the entire operating staff (Appendix Figure A.3 provides photographic examples).

[Table 4 about here]

This result presents a contrast to prior evidence on the impacts of information technology (IT) investments on centralization, which has found that IT facilitates increased spans of control (Bloom et al. 2012, 2014). Automation, however, is distinct. Because automation typically substitutes for labor in routine tasks, where machines have comparative advantage (Acemoglu and Restrepo 2018), and increases the returns to managerial discretion and judgment (Agrawal et al. 2018), automation investments may be more likely to reduce spans of control.

Collectively, this evidence suggests that automation was accompanied by a wide range of changes in AT&T's workforce, reflecting a reorganization of work under a new, mechanical call switching technology. We believe these changes are representative of others which we discussed in Section 3 but are more difficult to systematically measure. In Appendix D, we also establish the robustness of these results to other difference-in-differences estimation methods suggested in recent research (e.g., Borusyak et al. 2021, Callaway and Sant'Anna 2021).[16]

6 The Long Tail of Diffusion

Developing mechanical switching technology, and designing a new business model around it, ostensibly contributed to AT&T's initial 30-year delay in adoption. Even then, however, it took AT&T another 60 years to automate the rest of the telephone network. In this section we examine why, complementing Section 5 by studying the long tail of diffusion.

Our analysis will relate panel variation in cutovers across cities to market characteristics. We extend our city panel with additional census-derived measures, including the adult (16+) population (a measure of market size), demographic composition, and broader workforce characteristics, such as employment rates among young women and the fraction employed as operators (Feigenbaum and Gross 2022), which might proxy for labor market tightness.

6.1 Empirical evidence

We use these data to examine which cities were likely to have earlier cutovers: although the panel ends in 1940, the pre-1940 variation can point to underlying forces explaining delays in adoption. Table 5 shows average 1910 characteristics of cities which had their first cutover before 1920, after 1940, and in five-year intervals in between. The city characteristics in this table include the adult population; the fraction of this population employed (overall and as operators); and the same for young (16-25), white American-born women (the main demographic AT&T hired from; denoted 'f/n/w/y'). The most striking pattern is that cities with earlier cutovers are much larger than those with later cutovers, especially in the AT&T (post-1920) cutover era.

[Table 5 about here]

[16] Recent papers have highlighted potential drawbacks of standard two-way fixed effects (TWFE) models in estimating difference-in-differences with staggered treatment, especially if there is treatment effect heterogeneity or dynamic effects, and if most or all of the sample is treated. To a first order, we do not expect these threats to be problematic in our setting, since 90% of the cities in our sample are untreated when the sample ends, and because the narrative evidence makes clear that this shock had immediate (rather than time-varying) effects on telephone companies. Confirming this intuition, we find similar results with TWFE-robust estimators.

In Table 6 we evaluate these patterns in a multivariate context. We estimate the following cross-city regression, while controlling for state fixed effects (α_s):

$$Y_i = X_i\beta + \alpha_s + \varepsilon_i \tag{2}$$

where i indexes cities, and Y_i is an indicator for whether a city has a pre-1940 cutover (Columns 1 to 2) or the year of a city's first cutover (Columns 3 to 4), and X_i includes the city characteristics in Table 5. The sequence of automation is primarily explained by market size: a doubling of city population is associated with a 12.5% higher probability of automation before 1940, with t-statistics of nearly 20, though this disguises 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 all others.

[Table 6 about here]

Table 6 does not indicate a relationship between cutovers and young women's employment rates, indicating that automation was not more likely in cities with tighter labor markets for young women. In Appendix D, we complement these results with evidence on trends, reproducing figures from Feigenbaum and Gross (2022). Using an event study design (analogous to Equation (1), but with time-varying parameters), we find that young women's employment rates were not changing prior to cutovers, though telephone operation's share of young women's employment was growing rapidly—suggesting that automation was not related to labor market tightness broadly, but rather attributable to AT&T's own fast-growing labor demand.

6.2 Explaining the Long Tail

The patterns in Tables 5 and 6 connect closely to our theoretical structure in Section 4. Recall 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. We return to our monopolist firm in Section 4, which produced Q widgets under a manual technology with constant marginal costs $c = (1-\beta)n^2$, such that $VC(Q) = cQ$. An automated system, by comparison, has $c' < c$ (with $c' = (1-\alpha-\beta)n^2$), and costs $FC = (1+n)\theta$ to implement. If total costs $FC + VC = (1+n)\theta + c'Q < cQ$, 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 $VC(Q) = cQ^{\varphi}$, where $\varphi > 0$ is a constant; when $\varphi > 1$, marginal costs are increasing in Q, and when $\varphi < 1$, 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, as the last subscriber adds relatively little value (in the form of new connections) to existing ones (who already enjoy a large stock).[17]

With Q subscribers, a telephone network has $\frac{Q(Q-1)}{2}$ potential connections. If the cost of manually servicing each connection is c, the effect of adding an additional $(Q+1)$th subscriber is to introduce Q new possible connections, at cost cQ; in other words, marginal costs increase linearly in the network size. We can thus characterize $VC(Q)$ for a telephone service company to be approximately quadratic in Q, with $VC(Q) = c \cdot \frac{1}{2}Q^2$. Automated switching is still a technology that reduces c (to c'), 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 $(c - c')\frac{Q^2}{2}$, and just like costs themselves, these cost savings increase quadratically in firm size. As a result, the largest markets will experience dramatically larger savings from the new technology.

To close the argument, we need to introduce dynamics. The final piece we consider is that markets may grow and/or the technology improve over time. Because the impact of market size on adoption is straightforward, here we will focus on technology. We discussed in Section 4 how technological improvements can be important to overcoming early challenges in adopting automation. Now we relate them to the long tail of diffusion. Let us characterize the automation technology as having a cost savings effect of $\alpha(t) = (1 - \beta) \cdot (1 - \exp^{-t})$, such that at time $t = 0$ it has zero impact and at the limit generates savings of $1 - \beta$, reducing marginal costs to zero (since $\lim_{t\to\infty} c'(t) = \lim_{t\to\infty}(1 - \alpha(t) - \beta)n^2 = 0$). Even if c' were linear in t, it would take a much longer time for the productivity benefits of automation in smaller markets to match that achieved by larger markets, by virtue of the fact that the marginal 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 lags in adoption in large versus small markets are likely to be even greater.

Thus, economies of scale vis-à-vis fixed costs were not the only force making automation relatively more attractive to AT&T in large, urban markets: even more important is that marginal costs grew rapidly in the size of the firm, compounding the cost savings. This on its own might explain AT&T's long lags in adoption in larger and smaller markets. When technology improvements also

[17] 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.

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 that AT&T was well-positioned for technology adoption—including via its vertical integration, scale in manufacturing, access to capital, full information, and a powerful corporate center—it took the firm nearly a century to automate telephone call switching. We argue these long delays are at least in part attributable to organizational and economic obstacles. With regards to the former, the interdependencies of call switching with other elements of AT&T's technology and production systems made replacing them a challenging undertaking, and required both technological and organizational innovation. Once automation got underway, scale economies in AT&T's local markets play a large role in explaining its progression thereafter.

This paper is effectively a case study, and to some readers, AT&T may seem a quite specific case. In many ways it is: AT&T was the largest U.S. employer for most of the twentieth century, a paragon for corporate strategy, and the paradigm of regulated monopolies. The first two characteristics we view as strengths for research, as they open up opportunities to study its adoption of automatic call switching holding many otherwise important factors fixed (like those named above). With increasing concentration in the product and labor market today, especially among high-tech firms operating in complex, networked industries, understanding what causes and challenges automation in these settings is increasingly valuable. If nothing else, we believe its sheer size and outsized role in business and economic history makes it intrinsically important.

Two hesitations nevertheless remain. The first is the question of whether AT&T (or more broadly, the U.S. market) was distinctive in the length of time it took to automate telephone service. Looking abroad, it would appear not: the first automatic exchange in the United Kingdom was opened in 1912, and the last manual exchange ceased service in 1976. Likewise, in Australia, the analogous events were in 1912 and 1991. Both of these countries had different commercial and regulatory environments from the U.S. (in both cases, telephone service was administered by state-owned postal service organizations), yet they faced similarly-long delays.

The second hesitation is AT&T's position as a regulated monopoly: AT&T not only faced little competition in most of the markets it served, but it was also governed by rate of return (RoR) regulation—both of which could depress incentives for cost-saving capital investment. Ironically, but consistent with twentieth century experience with RoR regulation, this rate-setting structure encouraged high capital-to-labor ratios through which the firm could justify requests for higher rates. We see this ourselves in newspaper reporting, where cutovers were often accompanied by rate increases "because of added expense of the dial system" or "to cover the installation cost" (see Appendix Figure A.6 for examples). More generally, regulatory arbitrage created loopholes to RoR regulation. As Mueller (1997) explains, local and long-distance service were provided through the same infrastructure, with system-level costs, but because their prices were independently regulated (by state and federal regulators, respectively), AT&T shifted fixed costs to more strictly-regulated jurisdictions—namely, the states—as justification for higher rates.

Given these incentives, the delays in automation would seem to require other explanations. Moreover, if margins were truly fixed by the regulatory standard, the only way for the firm to grow profits would be to grow the business. Indeed, network growth had been one of the firm's main objectives since Theodore Vail (AT&T's then-CEO) set its sights on universal service in 1907 (Mueller 1997). As we have documented, manual switching technology was widely seen inside and outside of the firm as the main obstacle to AT&T's continued expansion in the period we study. Even a profit-maximizing monopolist might want to eliminate these bottlenecks.

A question more difficult to resolve is the effects of AT&T's lack of competition on the pace of automation, especially without a counterfactual to compare against. On the one hand, we might expect these effects to be muted, since its market power was constrained by regulation. On the other, competition ostensibly could have spurred faster investments in quality-enhancing or cost-saving (and thus price-reducing) technology, in the quest for share. A consequence of competition, however, would be lower volume, as AT&T and its competitors split the market—which could endogenously undermine the profitability of investments in automation. Based on recent evidence, we think the latter scenario is most likely. In what seems a reasonable analogy for AT&T's technology adoption problem, Macher et al. (2021) show that cement plants with greater competition are less likely to upgrade to fuel-efficient kilns, attributing this to the difficulty of recouping the sunk costs of the investment because competition reduces their equilibrium output.

Caveats aside, we think this example can be a parable for some automation and technology adoption problems today.[18] The challenge of incorporating new technology into existing systems may partly explain why an AI-driven wave of automation has not yet come to pass. Consistent with a task-based systems view, Bresnahan (2021) argues that AI's most valuable applications are unlikely to substitute for labor in isolated tasks, but rather will involve the design of new systems around them. Agrawal et al. (2022) provide examples of this challenge, such as for the use of AI in health care, and argue that the frictions of interdependencies can explain why AI has been adopted relatively quickly for some narrow problems like product recommendations and financial fraud detection, whereas more slowly in complex settings like innovation and drug discovery. The AT&T example embodies the type of systems challenges that both they and Bresnahan (2021) describe as instrumental to AI having its full effect on firm performance.

Beyond AI, there is a wide range of settings where the tensions in this paper would likely apply. In the 1960s, for example, the U.S. Internal Revenue Service (IRS) began adopting automatic data processing (ADP) to replace manual tax return processing, driven by massive growth in the volume of returns and complexity of the tax code, which challenged manual methods. ADP required not only the installation of computers, but also a new taxpayer identification system, a relocation of activity from satellite branches to central offices, changes in organization, and more. A 1964 report describes the breadth of challenges this presented (BLS 1964):

> The application of ADP to tax information handling required more than the replacement of conventional methods with electronic computing equipment. The "total systems approach" to data processing was adopted, and plans were made for extensive changes in work flow, services to taxpayers, and location of jobs. In short, the introduction of ADP required a review of the total functions and organization of the entire IRS.

We can also see examples in other industries. The automation of bank tellers changed the operation and function of consumer bank branches (Bessen 2015). Containerization replaced longshoremen with mechanical cranes, but required massive complementary investment in ships, containers, ports, and high-skill labor. These are but a few such examples. What they share in common, however, is that the task being automated—tax return processing, bank telling, and cargo loading, in these cases—was routine yet intertwined with other firm activities.

Several interesting tensions remain. One is a dynamic tradeoff of vintage technologies with learning curves, where a replacement technology may initially entail higher costs but offers a possibility of future savings as firms learn to use them productively—a phenomenon we see with AT&T. Firms with shorter investment horizons (e.g., due to fast-changing markets) may not be able to make this tradeoff as AT&T could. Another question concerns the interaction of automation with scale,

[18] It also remains one for understanding the past: Juhász et al. (2020), for example, observe patterns of reorganization around the adoption of mechanized cotton spinning in France in the Industrial Revolution.

and the degree to which automation reinforces winner-take-all industry dynamics. We believe these questions are ripe for further attention, and note that historical examples can often provide a useful laboratory for these contemporary problems, with opportunities to access primary data and study long-run outcomes that only the passage of time allows.

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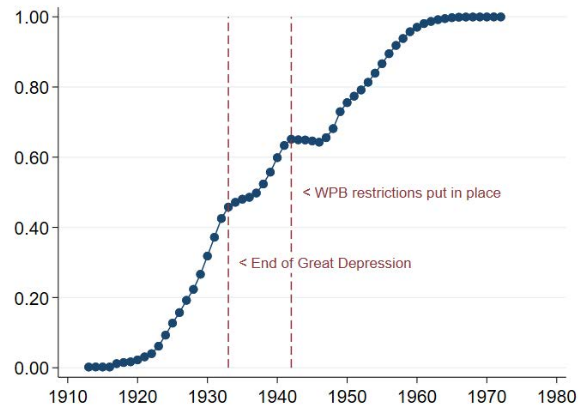
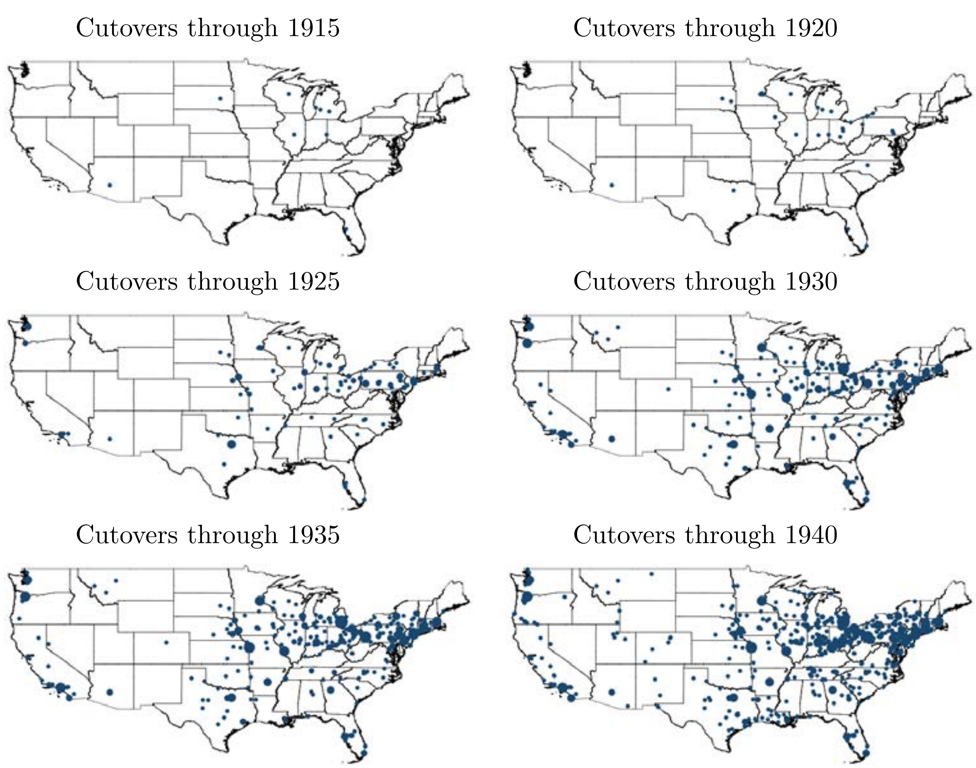
Figure 1: Percent of Bell system on dial, 1913-1972



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. The S-curve includes two temporary slowdowns: one following the Great Depression, during which few new cutovers were planned, and one during World War II, following government restrictions on the use of copper due to supply shortages, which effectively halted new installations.

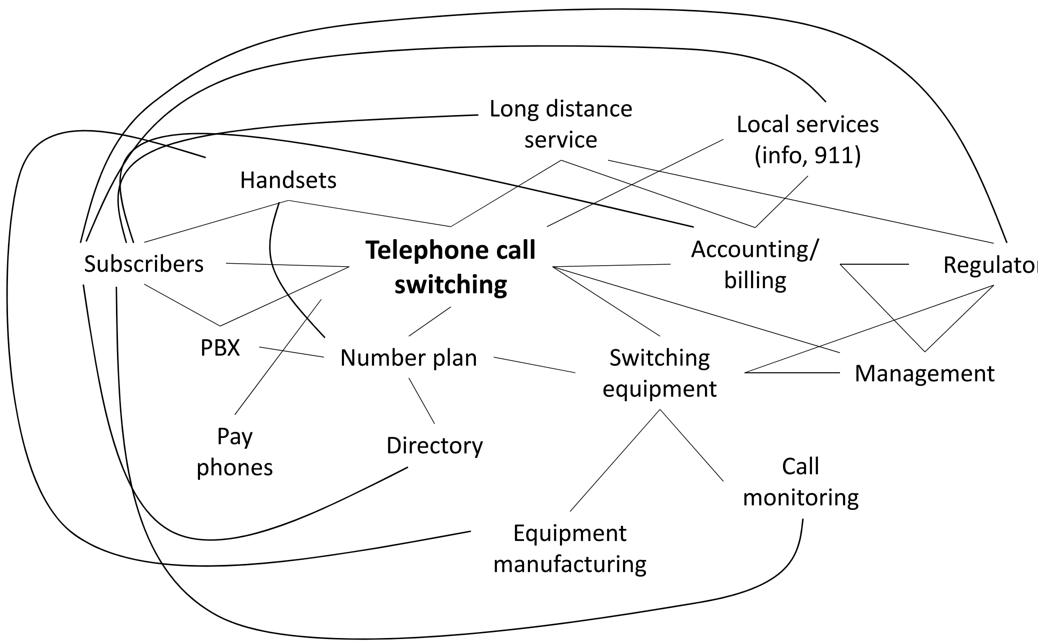
Figure 2: Cities with cutovers in Newspapers data, in 5-year intervals, 1915-1940 (bubble sizes proportional to number of cutovers)



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 number 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

<u>AT&T Corporate</u>
–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

<u>Regulators</u>
–Telephone rate changes
–Public concerns

<u>Central Offices</u>
–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

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

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

Table 1: Characteristics of U.S. telephone industry, 1902-1937

	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, 1902-1937. 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: Principal occupations in the telephone industry, 1910-1940

	1910		1920		1930		1940		
Occupation	Rank	Percent	Rank	Percent	Rank	Percent	Rank	Percent	Pct. Female
Telephone operators	1	54.1%	1	65.4%	1	55.3%	1	55.4%	94.6%
Linemen, servicemen	2	12.4%	2	10.5%	2	13.5%	2	19.0%	1.3%
Clerical workers	4	5.4%	3	6.4%	3	9.2%	3	6.9%	57.3%
Electricians	3	7.0%	4	3.0%	8	1.6%	22	0.2%	0.4%
Bookkeepers	6	3.2%	5	2.4%	9	1.3%	7	1.7%	63.1%
Typists, secretaries	8	1.8%	6	2.1%	5	3.0%	18	0.3%	96.0%
Managers (n.e.c.)	5	3.7%	7	1.9%	4	3.0%	6	2.6%	24.1%
Laborers (n.e.c.)	7	2.7%	8	1.5%	7	2.4%	24	0.1%	3.9%
Electrical engineers	34	0.0%	9	0.8%	6	2.6%	4	3.0%	0.9%
Inspectors (n.e.c.)	10	1.3%	10	0.8%	14	0.5%	14	0.5%	17.6%

Notes: Table lists top 10 occupations in the telephone industry in 1920 and their fraction of (nationwide) industry employment in each decade from 1910 to 1940. We restrict the sample to working-age adults (age 16 to 65) in each census who live populated cities (as we measure them; see Section 5) and report working in the telephone industry. Sample excludes workers with unknown occupation. The table also reports the share of telephone industry workers in each occupation that are women.

Table 3: Effects of dial on the occupational structure of the telephone industry

	Ln(Female ...)				Ln(Male ...)		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Operators	Clerks	Bookkeepers	Electricians	Electr. Engs.	Mechanics	Linemen
Post-cutover	-0.443***	0.100***	0.054*	-0.108***	0.130***	0.069***	-0.040
	(0.035)	(0.036)	(0.033)	(0.033)	(0.038)	(0.022)	(0.038)
N	10852	10852	10852	10852	10852	10852	10852
R^2	0.88	0.74	0.55	0.63	0.72	0.47	0.79
Y mean	2.244	0.281	0.215	0.240	0.159	0.042	1.219

Notes: Table presents results from a DID regression estimating the effects of local dial adoption on (log) employment in select occupations in the telephone industry. *, **, *** represent significance at the 0.1, 0.05, and 0.01 levels, respectively. SEs clustered by city in parentheses.

Table 4: Changes in the operating force and managerial employment

Panel A: Composition of telephone operators				
	Ln(Fem. operators)			
	(1)	(2)	(3)	(4)
	Age 16-25	Age 26+	Average age	Share 26+
Post-cutover	-0.536***	-0.326***	1.552***	0.061***
	(0.042)	(0.038)	(0.290)	(0.015)
N	10852	10852	10580	10580
R^2	0.82	0.84	0.69	0.63
Y mean	1.782	1.345	25.821	0.375
Panel B: Managerial employment				
	(1)	(2)	(3)	(4)
	Managers	Inspectors	All workers	Wrkrs:Mgrs
Post-cutover	0.088**	0.053**	-0.262***	-12.802***
	(0.036)	(0.024)	(0.027)	(2.515)
N	10852	10852	10852	4986
R^2	0.64	0.57	0.92	0.66
Y mean	0.489	0.085	2.785	22.293

Notes: Table presents results from a DID regression estimating the effects of local dial adoption on the composition of the telephone operating force (Panel A) and employment in managerial and quality control occupations (Panel B), including managers and service inspectors. *, **, *** represent significance at the 0.1, 0.05, and 0.01 levels, respectively. SEs clustered by city in parentheses.

Table 5: 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)
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 is 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 6: City characteristics and the pace of automation

	Any cutover by 1940?		Timing of earliest cutover	
	(1)	(2)	(3)	(4)
Ln(Population 16+)	0.134***	0.132***	-1.744***	-1.852***
	(0.007)	(0.007)	(0.198)	(0.213)
F/n/w/y pct. working		0.001		0.043
		(0.001)		(0.042)
F/n/w/y pct. operators		-0.004		-0.253
		(0.006)		(0.360)
N	2991	2991	324	324
R^2	0.24	0.24	0.28	0.28
Y Mean	0.11	0.11	1929.08	1929.08

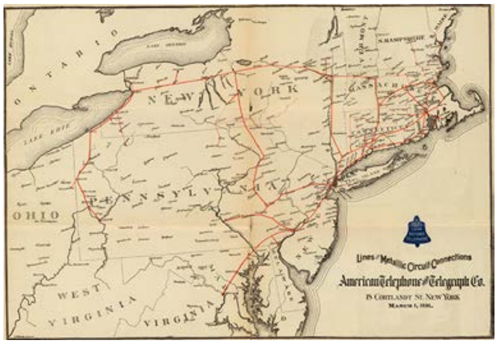
Notes: Table reports estimates from a regression of an indicator for whether a given city has a cutover in our data by April 1, 1940 (Columns 1 to 2) and the timing of the earliest cutover (Columns 3 to 4) on city characteristics in 1910. The sample for all columns omits cities with a cutover before 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 is shorthand for female, American-born, white/non-Hispanic, and young (age 16-25). *, **, *** represent significance at the 0.1, 0.05, and 0.01 levels, respectively. All specifications include state fixed effects. Robust SEs in parentheses.

Web Appendix

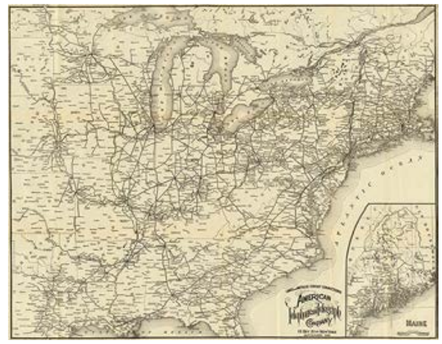
A Historical Appendix

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

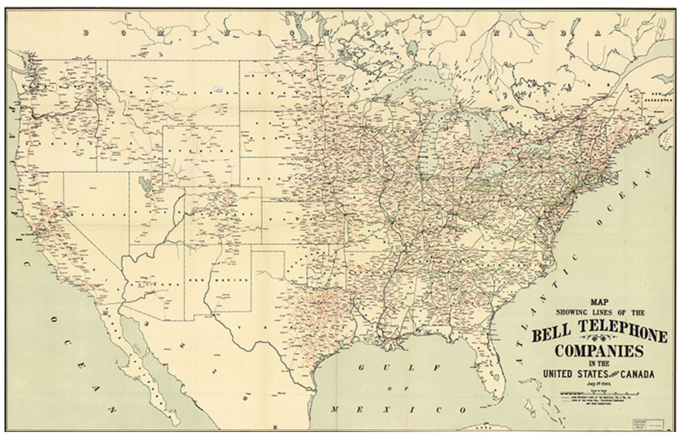
1891



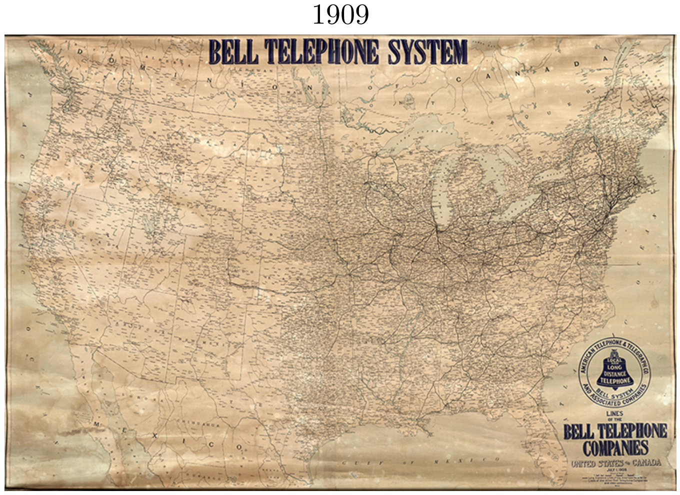
1898



1904

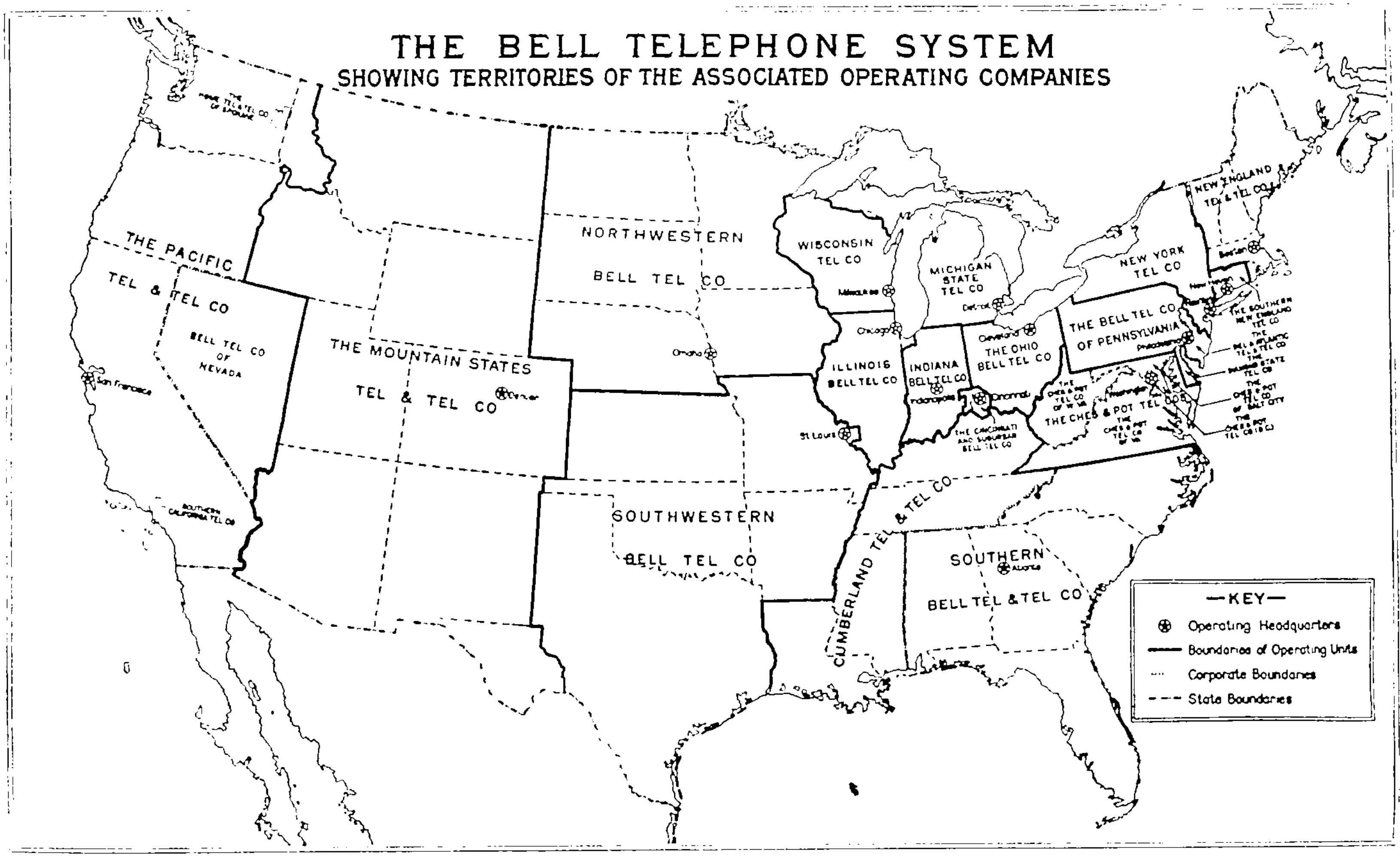


1909



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

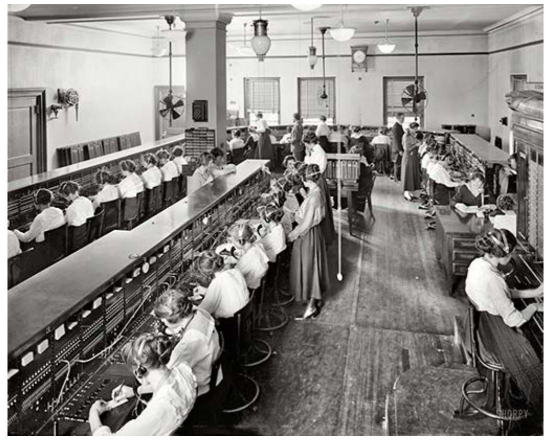


Notes: Figure marks the boundaries of the various Bell operating companies' territories across the united states, and the headquarters city for each. Map from AT&T's 1922 annual report.

Figure A.3: Photographs of switchboard operators

Salt Lake City, UT, 1913

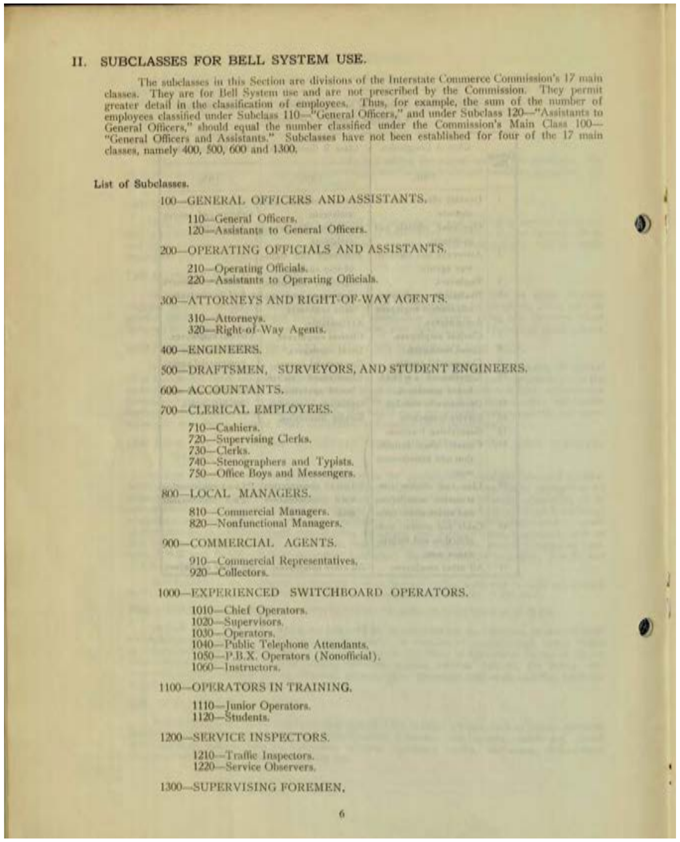
Washington, DC, 1919



Unknown location, 1943

Notes: Figure shows photographs of telephone operators at switchboards.

Figure A.4: AT&T Standard Occupational Classification (1917)



II. SUBCLASSES FOR BELL SYSTEM USE.

The subclasses in this Section are divisions of the Interstate Commerce Commission's 17 main classes. They are for Bell System use and are not prescribed by the Commission. They permit greater detail in the classification of employees. Thus, for example, the sum of the number of employees classified under Subclass 110—"General Officers," and under Subclass 120—"Assistants to General Officers," should equal the number classified under the Commission's Main Class 100—"General Officers and Assistants." Subclasses have not been established for four of the 17 main classes, namely 400, 500, 600 and 1300.

List of Subclasses.

100—GENERAL OFFICERS AND ASSISTANTS.
110—General Officers.
120—Assistants to General Officers.

200—OPERATING OFFICIALS AND ASSISTANTS.
210—Operating Officials.
220—Assistants to Operating Officials.

300—ATTORNEYS AND RIGHT-OF-WAY AGENTS.
310—Attorneys.
320—Right-of-Way Agents.

400—ENGINEERS.

500—DRAFTSMEN, SURVEYORS, AND STUDENT ENGINEERS.

600—ACCOUNTANTS.

700—CLERICAL EMPLOYEES.
710—Cashiers.
720—Supervising Clerks.
730—Clerks.
740—Stenographers and Typists.
750—Office Boys and Messengers.

800—LOCAL MANAGERS.
810—Commercial Managers.
820—Nonfunctional Managers.

900—COMMERCIAL AGENTS.
910—Commercial Representatives.
920—Collectors.

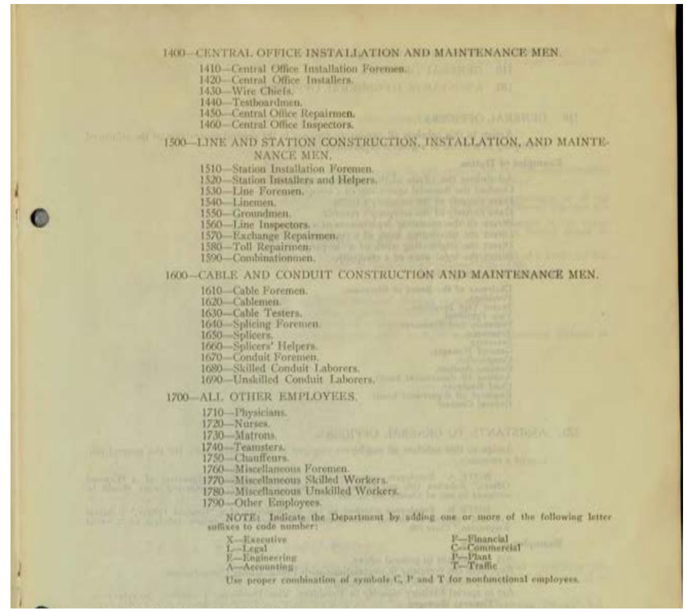
1000—EXPERIENCED SWITCHBOARD OPERATORS.
1010—Chief Operators.
1020—Supervisors.
1030—Operators.
1040—Public Telephone Attendants.
1050—P.B.X. Operators (Nonofficial).
1060—Instructors.

1100—OPERATORS IN TRAINING.
1110—Junior Operators.
1120—Students.

1200—SERVICE INSPECTORS.
1210—Traffic Inspectors.
1220—Service Observers.

1300—SUPERVISING FOREMEN.

6



1400—CENTRAL OFFICE INSTALLATION AND MAINTENANCE MEN.
1410—Central Office Installation Foremen.
1420—Central Office Installers.
1430—Wire Chiefs.
1440—Testboardmen.
1450—Central Office Repairmen.
1460—Central Office Inspectors.

1500—LINE AND STATION CONSTRUCTION, INSTALLATION, AND MAINTENANCE MEN.
1510—Station Installation Foremen.
1520—Station Installers and Helpers.
1530—Line Foremen.
1540—Linemen.
1550—Groundmen.
1560—Line Inspectors.
1570—Exchange Repairmen.
1580—Toll Repairmen.
1590—Combinationmen.

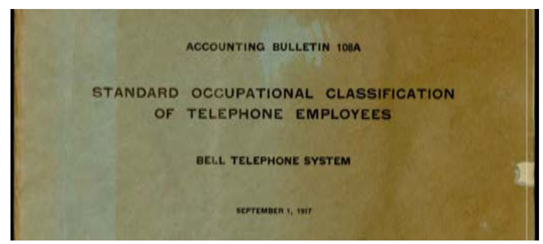
1600—CABLE AND CONDUIT CONSTRUCTION AND MAINTENANCE MEN.
1610—Cable Foremen.
1620—Cablemen.
1630—Cable Testers.
1640—Splicing Foremen.
1650—Splicers.
1660—Splicers' Helpers.
1670—Conduit Foremen.
1680—Skilled Conduit Laborers.
1690—Unskilled Conduit Laborers.

1700—ALL OTHER EMPLOYEES.
1710—Physicians.
1720—Nurses.
1730—Matrons.
1740—Teamsters.
1750—Chauffeurs.
1760—Miscellaneous Foremen.
1770—Miscellaneous Skilled Workers.
1780—Miscellaneous Unskilled Workers.
1790—Other Employees.

NOTE: Indicate the Department by adding one or more of the following letter suffixes to code number:

X—Executive
L—Legal
E—Engineering
A—Accounting
F—Financial
C—Commercial
P—Plant
T—Traffic

Use proper combination of symbols C, P and T for nonfunctional employees.



Notes: Figure provides excerpts from AT&T's Standard Occupational Classification as of September 1917, listing 17 major occupational classes (from 100–General Officers and Assistants to 1700–All Other Employees) and their subclasses. Bottom right figure is the source's title page (AT&T 1917).

Figure A.5: Sampling of newspaper headlines related to cutovers

Catalysts of mechanization:
Growth, capacity constraints

Reason for Change

The growth of Pensacola has been such that the capacity of the equipment in the present manual central office is about reached. No further additions can be made to this equipment, and it is necessary to establish a new central of greater capacity to care for future growth.

Pensacola News Journal, Pensacola, FL, 1931

One of the reasons for the change, according to Hirsch, is the increase in the volume of traffic and the length of time subscribers hold lines. This combination, Hirsch stated, results in lines being busy within the exchange itself in addition to slowing up the service.

"With the conversion to full dial operation," said Hirsch, "these busy lines will be very materially decreased, and instead of a capacity for 51 ,calls at any one time, there will be a capacity for 75 calls, an increase of 50 per cent. This should lead to vastly improved service."

Mansfield News-Journal, Mansfield, OH, 1941

Accompanying challenges:
Education, re-numbering, resistance

Hirsch said that the company would soon begin an educational program to instruct subscribers in the use of the dial. For this first year in the change-over both the old and new numbers will be listed in the telephone directory to be issued soon.

On the left of the subscriber's name will be a number marked "Call Manual" and on the right another number marked "Dial." If

Mansfield News-Journal, Mansfield, OH, 1941

Phone Hearing

A public hearing on the issue of dial telephones for Raleigh will be held before the State Utilities Commission on January 26 at 11 a. m., it was announced yesterday.

Mayor George A. Iseley recently received a petition sign- by a number of Raleigh residents who oppose the Southern Bell Telephone's plan to change from the battery system to the dial system in the near future.

Raleigh News and Observer, Raleigh, NC, 1939

Notes: Figure reproduces newspaper headlines and/or content from the following articles: "Telephone Company Explains Its Change to Dial Service," *The Pensacola News Journal* (Pensacola, FL), December 11, 1931; "Phone Hearing," *The Raleigh News and Observer* (Raleigh, NC), January 17, 1939; "Start First Dial Phones Here April 5," *The Mansfield News-Journal* (Mansfield, OH), March 28, 1941. All articles accessed from Newspapers.com.

Figure A.6: Sampling of newspaper headlines related to rate increases

The company is going to ask the public utilities commission for an increase in rates regardless of what type of equipment is installed in the new building.

The increase asked will be 33 1-3 per cent over the present rate for commercial telephones and 25 per cent over the present rate for residence telephones if new equipment of the present (manual operated) type is installed.

If automatic (dial) equipment is installed the increase asked will be 50 per cent over the present commercial rate and 37 1-2 per cent over the present residence rate.

Manhattan, KS, 1924

Application was filed with the state public service commission today by the Southwestern Bell Telephone Company for authority to install dial telephones at Hickman Mills, Martin City, Grandview and Dallas, all in Jackson county near Kansas City, and Norborne, Carroll county. A petition from telephoe subscribers in the towns asking for dial phones instead of the present magnetic system was filed with the application.

An agreement has been reached between the company and subscribers for a new schedule of rates for the dial phones, which will result in an increase for various classes of service. The phone company stated the rates would not be compensatory at present, but that it anticipates an increase in subscribers and development of the communities that later will justify them.

Various cities, MO, 1929

NASHVILLE, June 24 — Proposed rate increases in towns where Southern Bell is replacing manual with dial telephones will be investigated by the State Utilities Commission, Leon Jourolmon revealed here today.

Various cities, TN, 1939

TELEPHONE HEARING IS SCHDULED TODAY

Application of the Milledgeville Telephone and Telegraph Company to install dial telephones and increase rates will be given a public hearing this morning by the Georgia Public Service Commission.

The company requests authority to increase the Milledgeville busines phone rates $1 a month and residence phones 40 cents a month when the dials are installed.

Milledgeville, GA, 1939

ACTION of the City Commission in agreeing to an adjustment in telephone rates in Corpus Christi is in accordance with the Commission's resolution of May 6, 1937, prior to installation of the city's new dial telephone system.

Following passage of this resolution, the telephone company spent $1,117,000 erecting a new building, installing the most modern dial equipment available, extending and rebuilding the outside cable and wire network throughout the city, and furnishing dial telephones to all customers. Installation of the new system resulted in a net increase in the company's investment in the Corpus Christi telephone system of more than $700,000 or approximately 60 per cent.

Corpus Christi, TX, 1939

New Rates Planned

In agreeing to install the dial system in Tyler, the telephone company officials are asking authority of the City Commission to put a new rate schedule into effect, which will call for an increase in the telephone rates, but which will make the rates here on about an even par with those charged in other cities where the dial telephone system is in operation.

Tyler, TX, 1939

Volga, Bruce Unite in New 'Phone Plan

Installation of Dial System to Involve Slight Increase in Rates

Various cities, SD, 1940

Notes: Figure reproduces newspaper headlines and/or content from the following articles: "Proposed Telephone Rates," *The Morning Chronicle* (Manhattan, KS), April 24, 1924; "Ask Dial Service in Five Missouri Towns," *Jefferson City Post-Tribune* (Jefferson City, MO), August 22, 1929; "Jourolman to Probe Phone Rate Boosts," *The Knoxville News-Sentinel* (Knoxville, TN), June 25, 1939; "Telephone Rate Hearing is Set Today," *The Atlanta Constitution* (Atlanta, GA), December 20, 1939; "An Explanation of the Telephone Rate Adjustment," *The Corpus Christi Caller* (Corpus Christi, TX), October 6, 1939; "New Rates Planned," *The Tyler Courier-Times* (Tyler, TX), September 24, 1939; "Volga, Bruce Unite in New 'Phone Plan," *Argus-Leader* (Sioux Falls, SD), July 20, 1940. All articles accessed from Newspapers.com.

B Theoretical Appendix

B.1 Equilibrium prices, quantities, and profits, and regularity conditions

We solve for π^* as follows:

$$\begin{aligned}
\frac{\partial \pi}{\partial P} = Q(P) + (P-c)(Q'(P)) &= 0 \\
(M - aP) + (P-c)(-a) &= 0 \\
M - 2aP + ac &= 0
\end{aligned}$$

Hence $P^* = \frac{M+ac}{2a}$, $Q(P^*) = M - a\frac{M+ac}{2a} = \frac{M-ac}{2}$, and

$$\begin{aligned}
\pi^* &= (P^* - c) \cdot Q(P^*) - FC \\
&= \left(\frac{M+ac}{2a} - c\right)\frac{M-ac}{2} - FC \\
&= \left(\frac{M+ac}{2a} - \frac{2ac}{2a}\right)\left(\frac{M-ac}{2}\right) - FC \\
&= \left(\frac{M-ac}{2a}\right)\left(\frac{M-ac}{2}\right) - FC \\
&= \frac{(M-ac)^2}{4a} - FC
\end{aligned}$$

Embedded in these results is the necessary market size required for production to take place. Under manual production (where $c = (1-\beta)n^2$), the firm will only produce if:

$$\begin{aligned}
\frac{(M-ac)^2}{4a} &> 0 \\
\frac{(M-a(1-\beta)n^2)^2}{4a} &> 0 \\
M - a(1-\beta)n^2 &> 0 \\
M &> a(1-\beta)n^2
\end{aligned}$$

The analogous conditions for partial automation and full automation are:

$$\begin{aligned}
\text{Partial:} \quad & M > a(1 - \frac{1}{2}\alpha)n^2 + \sqrt{4a\theta} \\
\text{Full:} \quad & M > a(1 - \alpha - \beta)n^2 + \sqrt{4a(1+n)\theta}
\end{aligned}$$

We assume in Section 4 that M is large enough to meet these conditions.

B.2 Proofs

Lemma 1.

The returns to partial automation ($\Delta\pi_p$) and full automation ($\Delta\pi_f$) are:

$$\Delta\pi_p = \frac{1}{4}n^2\left[\left(2M - an^2\left(2 - \frac{1}{2}\alpha - \beta\right)\right)\left(\frac{1}{2}\alpha - \beta\right)\right] - \theta$$
$$\Delta\pi_f = \frac{1}{4}n^2\left[\left(2M - an^2\left(2 - \alpha - 2\beta\right)\right)\alpha\right] - (1+n)\,\theta$$

Proof:

The returns to partial automation (of the integral task), relative to no automation, are:

$$\begin{aligned}
\Delta\pi_p &= \frac{\left(M - a\left(1 - \frac{1}{2}\alpha\right)n^2\right)^2}{4a} - \frac{\left(M - a\left(1-\beta\right)n^2\right)^2}{4a} - \theta \\
&= \frac{1}{4a}\left[\left(M - a\left(1 - \frac{1}{2}\alpha\right)n^2\right)^2 - \left(M - a\left(1-\beta\right)n^2\right)^2 - 4a\theta\right] \\
&= \frac{1}{4a}\left[\left(M^2 - 2aM\left(1 - \frac{1}{2}\alpha\right)n^2 + a^2\left(1 - \frac{1}{2}\alpha\right)^2 n^4\right) - \right. \\
&\qquad \left.\left(M^2 - 2aM\left(1-\beta\right)n^2 + a^2\left(1-\beta\right)^2 n^4\right) - 4a\theta\right] \\
&= \frac{1}{4a}\left[2aMn^2\left(\left(1-\beta\right) - \left(1 - \frac{1}{2}\alpha\right)\right) + \right. \\
&\qquad \left. a^2n^4\left(\left(1 - \frac{1}{2}\alpha\right)^2 - \left(1-\beta\right)^2\right) - 4a\theta\right] \\
&= \frac{1}{4}n^2\left[2M\left(\frac{1}{2}\alpha - \beta\right) + an^2\left(-2\left(\frac{1}{2}\alpha - \beta\right) + \left(\frac{1}{2}\alpha\right)^2 - \left(\beta\right)^2\right)\right] - \theta \\
&= \frac{1}{4}n^2\left[2M\left(\frac{1}{2}\alpha - \beta\right) + an^2\left(-2\left(\frac{1}{2}\alpha - \beta\right) + \left(\frac{1}{2}\alpha + \beta\right)\left(\frac{1}{2}\alpha - \beta\right)\right)\right] - \theta \\
&= \frac{1}{4}n^2\left[2M\left(\frac{1}{2}\alpha - \beta\right) + an^2\left(-2 + \left(\frac{1}{2}\alpha + \beta\right)\right)\left(\frac{1}{2}\alpha - \beta\right)\right] - \theta \\
&= \frac{1}{4}n^2\left[\left(2M + an^2\left(-2 + \frac{1}{2}\alpha + \beta\right)\right)\left(\frac{1}{2}\alpha - \beta\right)\right] - \theta \\
&= \frac{1}{4}n^2\left[\left(2M - an^2\left(2 - \frac{1}{2}\alpha - \beta\right)\right)\left(\frac{1}{2}\alpha - \beta\right)\right] - \theta
\end{aligned}$$

The returns to complete automation (of all tasks), relative to no automation, are:

$$\begin{aligned}
\Delta\pi_f &= \frac{\left(M - a\left(1-\alpha-\beta\right)n^2\right)^2}{4a} - \frac{\left(M - a\left(1-\beta\right)n^2\right)^2}{4a} - \left(1+n\right)\theta \\
&= \frac{1}{4a}\left[\left(M - a\left(1-\alpha-\beta\right)n^2\right)^2 - \left(M - a\left(1-\beta\right)n^2\right)^2 - 4a\left(1+n\right)\theta\right] \\
&= \frac{1}{4a}\left[\left(M^2 - 2aM\left(1-\alpha-\beta\right)n^2 + a^2\left(1-\alpha-\beta\right)^2 n^4\right) - \right. \\
&\qquad \left. \left(M^2 - 2aM\left(1-\beta\right)n^2 + a^2\left(1-\beta\right)^2 n^4\right) - 4a\left(1+n\right)\theta\right] \\
&= \frac{1}{4a}\left[2aMn^2\left(\left(1-\beta\right) - \left(1-\alpha-\beta\right)\right) + \right. \\
&\qquad \left. a^2n^4\left(\left(1-\alpha-\beta\right)^2 - \left(1-\beta\right)^2\right) - 4a\left(1+n\right)\theta\right] \\
&= \frac{1}{4}n^2\left[2M\left(\alpha\right) + an^2\left(\left(\left(1-\beta\right)-\alpha\right)^2 - \left(1-\beta\right)^2\right)\right] - \left(1+n\right)\theta \\
&= \frac{1}{4}n^2\left[2M\left(\alpha\right) + an^2\left(-2\left(\alpha\right)\left(1-\beta\right) + \left(\alpha\right)^2\right)\right] - \left(1+n\right)\theta \\
&= \frac{1}{4}n^2\left[2M\left(\alpha\right) + an^2\left(-2\left(1-\beta\right) + \left(\alpha\right)\right)\alpha\right] - \left(1+n\right)\theta \\
&= \frac{1}{4}n^2\left[\left(2M + an^2\left(-2+\alpha+2\beta\right)\right)\alpha\right] - \left(1+n\right)\theta \\
&= \frac{1}{4}n^2\left[\left(2M - an^2\left(2-\alpha-2\beta\right)\right)\alpha\right] - \left(1+n\right)\theta
\end{aligned}$$

Proposition 1.

Suppose $\frac{1}{2}\alpha > \beta$. The returns to partial automation are then increasing in M and α and decreasing in β and θ. The returns to full automation are increasing in M, α, and β, and decreasing in θ. The effects of increasing n (the cardinality of the production activity set) are positive for partial automation and ambiguous for full automation.

Proof:

The comparative statics of $\Delta\pi_p$ are as follows:

$$\frac{\partial \Delta\pi_p}{\partial n} = n\left[M - an^2\left(2 - \frac{1}{2}\alpha - \beta\right)\right]\left(\frac{1}{2}\alpha - \beta\right) > 0$$
$$\frac{\partial \Delta\pi_p}{\partial M} = \frac{1}{2}n^2\left(\frac{1}{2}\alpha - \beta\right) > 0$$
$$\frac{\partial \Delta\pi_p}{\partial \theta} = -1 < 0$$
$$\frac{\partial \Delta\pi_p}{\partial \alpha} = \frac{1}{4}n^2\left(M - an^2\left(1 - \frac{1}{2}\alpha\right)\right) > 0$$
$$\frac{\partial \Delta\pi_p}{\partial \beta} = -\frac{1}{2}n^2\left(M - an^2\left(1 - \beta\right)\right) < 0$$

The comparative statics of $\Delta\pi_f$ are as follows:

$$\frac{\partial \Delta\pi_f}{\partial n} = n\left[M - an^2\left(2 - \alpha - 2\beta\right)\right]\alpha - \theta \gtreqless 0$$
$$\frac{\partial \Delta\pi_f}{\partial M} = \frac{1}{2}n^2\alpha > 0$$
$$\frac{\partial \Delta\pi_f}{\partial \theta} = -\left(1 + n\right) < 0$$
$$\frac{\partial \Delta\pi_f}{\partial \alpha} = \frac{1}{2}n^2\left(M - an^2\left(1 - \alpha - \beta\right)\right) > 0$$
$$\frac{\partial \Delta\pi_f}{\partial \beta} = \frac{1}{2}an^4\alpha > 0$$

Proposition 2.

When $\beta > \frac{1}{2}\alpha$, partial automation is not an equilibrium outcome at any θ.

Proof:

Recall that the returns to partial automation are:

$$\Delta\pi_p = \frac{1}{4}n^2\left[\left(2M - an^2\left(2 - \frac{1}{2}\alpha - \beta\right)\right)\left(\frac{1}{2}\alpha - \beta\right)\right] - \theta$$

Under regularity conditions we assumed that $M > \max\{a\left(1 - \frac{1}{2}\alpha\right)n^2, a\left(1-\beta\right)n^2\}$. By implication, $\left(2M - an^2\left(2 - \frac{1}{2}\alpha - \beta\right)\right) > 0$, because when $\beta > \frac{1}{2}\alpha$:

$$\begin{aligned}\left(2M - an^2\left(2 - \frac{1}{2}\alpha - \beta\right)\right) &= 2\left(M - a\left(1 - \frac{1}{4}\alpha - \frac{1}{2}\beta\right)n^2\right)\\ &= 2\left(M - a\left(1 - \frac{1}{2}\left(\frac{1}{2}\alpha + \beta\right)\right)n^2\right)\\ &> 2\left(M - a\left(1 - \frac{1}{2}\alpha\right)n^2\right)\\ &> 0\end{aligned}$$

When $\beta > \frac{1}{2}\alpha$, $\left(\frac{1}{2}\alpha - \beta\right) < 0$. Because $\left(\frac{1}{2}\alpha - \beta\right) < 0$ multiplies a positive first term in $\Delta\pi_p$, all terms in $\Delta\pi_p$ are negative, and thus $\Delta\pi_p < 0$.

Proposition 3.

When α is small relative to θ, full automation is not an equilibrium outcome.

Proof:

Recall that the returns to full automation are:

$$\Delta\pi_f = \frac{1}{4}n^2\left[\left(2M - an^2\left(2 - \alpha - 2\beta\right)\right)\alpha\right] - (1+n)\theta$$

Under regularity conditions we assumed that $M > \max\{a\left(1 - \frac{1}{2}\alpha\right)n^2, a\left(1-\beta\right)n^2\}$. By implication, $\left(2M - an^2\left(2 - \alpha - 2\beta\right)\right) > 0$, because:

$$\begin{aligned}\left(2M - an^2\left(2 - \alpha - 2\beta\right)\right) &= 2\left(M - a\left(1 - \frac{1}{2}\alpha - \beta\right)n^2\right)\\ &> 2\left(M - a\left(1 - \frac{1}{2}\alpha\right)n^2\right)\\ &> 0\end{aligned}$$

Thus, because α multiplies a positive first term in $\Delta\pi_f$, holding θ fixed, we have $\lim_{\alpha\to 0}\Delta\pi_f < 0$ (or conversely, holding α fixed, $\lim_{\theta\to\infty}\Delta\pi_f < 0$).

B.3 Other, non-conforming scenarios

The body of the paper notes (in a footnote) a fifth automation scenario which it does not explicitly consider: automation of some, but not all, production tasks. In this subsection we demonstrate why this choice is strictly dominated by others in the choice set.

To formalize the argument, suppose the firm may automate $x < n$ production tasks, at a cost $x\theta$. In this case, firm profits will be as follows:

$$\pi_x = \frac{1}{2a}\left(M - an^2\left[\frac{x}{n}(1-\frac{1}{2}\alpha) + \frac{n-x}{n}(1-\beta)\right]\right)^2 - x\theta$$

By comparison, profits with no automation (0) or automation of the integral task only (p) are:

$$\begin{aligned}\pi_0 &= \frac{1}{2a}\left(M - an^2(1-\beta)\right)^2 - 0\\ \pi_p &= \frac{1}{2a}\left(M - an^2(1-\frac{1}{2}\alpha)\right)^2 - \theta\end{aligned}$$

Let us first assume that $\beta > \frac{1}{2}\alpha$ (i.e., congruence is more valuable than task-level cost savings of automation). In that case, we have $1-\beta < 1-\frac{1}{2}\alpha$. In turn,

$$\begin{aligned}x(1-\beta) &< x(1-\frac{1}{2}\alpha)\\ n(1-\beta) &< x(1-\frac{1}{2}\alpha) + (n-x)(1-\beta)\\ 1-\beta &< \frac{x}{n}(1-\frac{1}{2}\alpha) + \frac{n-x}{n}(1-\beta)\end{aligned}$$

We consequently have the following two conditions met:

$$\begin{aligned}\frac{1}{2a}\left(M - an^2(1-\beta)\right)^2 &> \frac{1}{2a}\left(M - an^2\left[\frac{x}{n}(1-\frac{1}{2}\alpha) + \frac{n-x}{n}(1-\beta)\right]\right)^2\\ 0 &< x\theta\end{aligned}$$

As a result, $\pi_0 > \pi_x$, and the scenario is strictly dominated by no automation. By the same method, we can show that if $\beta < \frac{1}{2}\alpha$, then $\pi_p > \pi_x$, and the scenario is strictly dominated by automation of the integral task. It is thus never an equilibrium outcome.

C Data Appendix

Note: This appendix parallels (and at times replicates) the data appendix of Feigenbaum and Gross (2022), "Answering the Call of Automation: How the Labor Market Adjusted to the Mechanization of Telephone Operation," 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.

C.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.

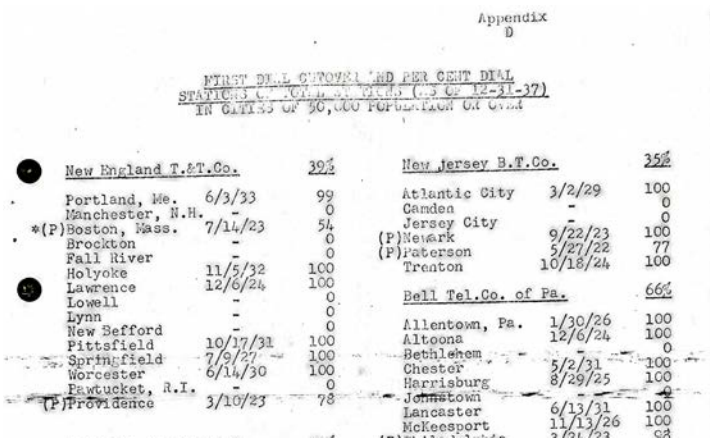
Data from AT&T's corporate archives

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

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



Appendix D

FIRST D[illegible] CUTOVE[illegible] 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 Bedford	-	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

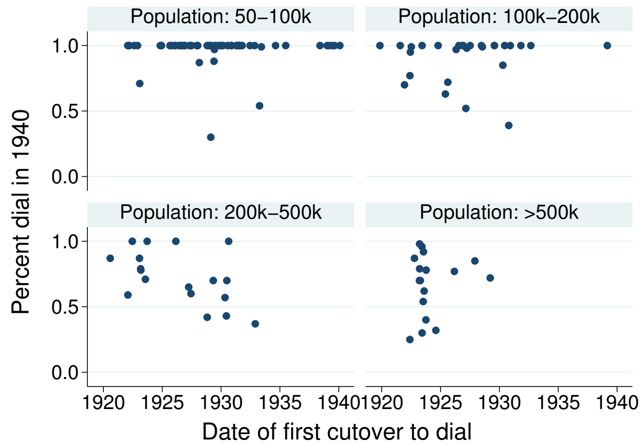
Bell Tel.Co. of Pa.		66%
Allentown, Pa.	1/30/26	100
Altoona	12/6/24	100
Bethlehem	-	0
Chester	5/2/31	100
Harrisburg	8/29/25	100
Johnstown	-	0
Lancaster	6/13/31	100
McKeesport	11/13/26	100

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 C.2 and C.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.

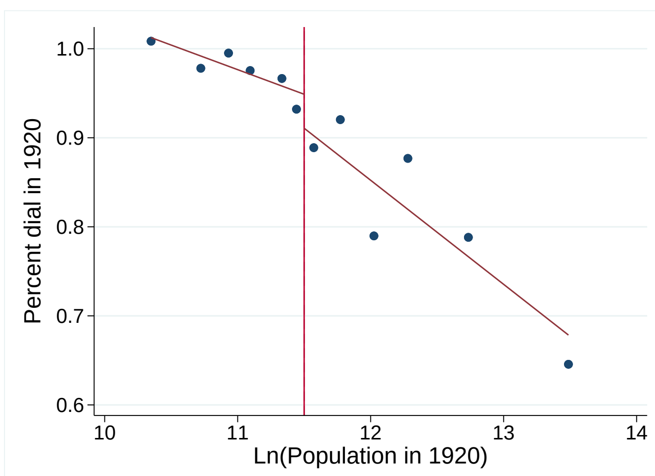
[2]This document was found in AT&T Archives and History Center box 106-10-02-07.

Figure C.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 C.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

[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

[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 C.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—Cut-over 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:

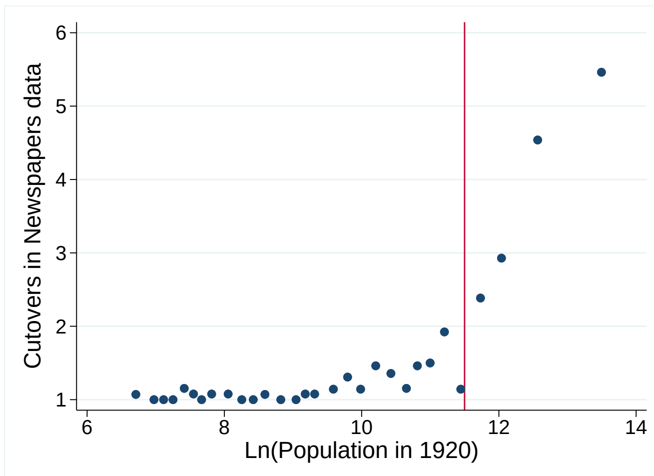
		Articles	
Category	Label	Count	Percent
1	Exact date provided	2,171	56.2
2	Date inferred from coarse information + other reports	1,150	29.8
3	Month and year provided or approximated	308	8.0
4	Year provided, past or present	25	0.7
5	Year provided, future	9	0.2
6	No timing information provided	196	5.1
Total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

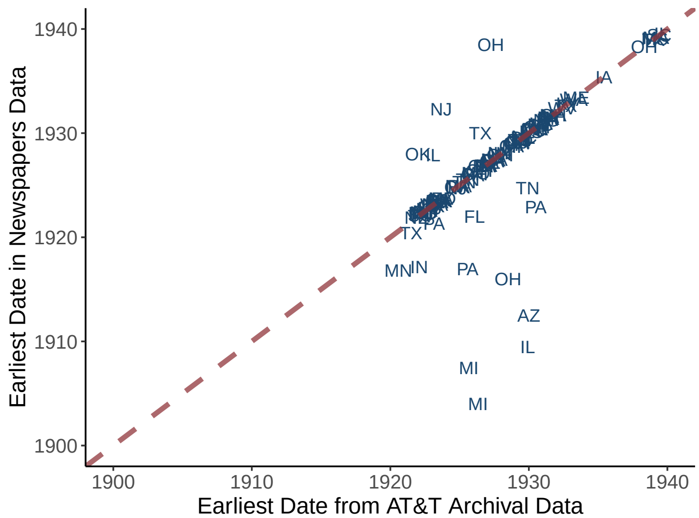
Comparison of AT&T and Newspapers data

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 C.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

[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 C.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.

C.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

[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 $\geq$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.

C.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.

D Supplementary Results

D.1 Robust TWFE estimation

Appendix Tables D.1 to D.4 present robustness checks on Tables 3 and 4 of the paper, evaluating their robustness to alternative two-way fixed effects estimation methods, as suggested by recent developments in applied econometrics. See Section 5 for discussion.

Table D.1: Effects of dial on the occupational structure of the telephone industry

	Ln(Female ...)			Ln(Male ...)			
	(1) Operators	(2) Clerks	(3) Bookkeepers	(4) Electricians	(5) Electr. Engs.	(6) Mechanics	(7) Linemen
Post-cutover	-0.461***	0.124***	0.049	-0.143***	0.184***	0.097***	-0.042
	(0.034)	(0.040)	(0.038)	(0.040)	(0.045)	(0.026)	(0.043)
N	10852	10852	10852	10852	10852	10852	10852
Y mean	2.244	0.281	0.215	0.240	0.159	0.042	1.219

Notes: Table presents results from a DID regression estimating the effects of local dial adoption on (log) employment in select occupations in the telephone industry. The table provides results estimated using the estimation method of Borusyak et al. (2021). *, **, *** represent significance at the 0.1, 0.05, and 0.01 levels, respectively. SEs clustered by city in parentheses.

Table D.2: Changes in the operating force and managerial employment

	Panel A: Composition of telephone operators			
	Ln(Fem. operators)			
	(1) Age 16-25	(2) Age 26+	(3) Average age	(4) Share 26+
Post-cutover	-0.560***	-0.340***	1.680***	0.066***
	(0.042)	(0.039)	(0.273)	(0.014)
N	10852	10852	10584	10584
Y mean	1.782	1.345	25.820	0.375
	Panel B: Managerial employment			
	(1) Managers	(2) Inspectors	(3) All workers	(4) Wrkrs:Mgrs
Post-cutover	0.092**	0.074***	-0.274***	-13.215***
	(0.040)	(0.027)	(0.028)	(2.905)
N	10852	10852	10852	5503
Y mean	0.489	0.085	2.785	21.181

Notes: Table presents results from a DID regression estimating the effects of local dial adoption on the composition of the telephone operating force (Panel A) and employment in managerial and quality control occupations (Panel B), including managers and service inspectors. The table provides results estimated using the estimation method of Borusyak et al. (2021). *, **, *** represent significance at the 0.1, 0.05, and 0.01 levels, respectively. SEs clustered by city in parentheses.

Table D.3: Effects of dial on the occupational structure of the telephone industry

	Ln(Female ...)			Ln(Male ...)			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Operators	Clerks	Bookkeepers	Electricians	Electr. Engs.	Mechanics	Linemen
Post-cutover	-0.397***	0.030	0.032	-0.103**	0.089*	0.092***	0.059
	(0.042)	(0.050)	(0.050)	(0.048)	(0.048)	(0.034)	(0.052)
N	10852	10852	10852	10852	10852	10852	10852
Y mean	2.244	0.281	0.215	0.240	0.159	0.042	1.219

Notes: Table presents results from a DID regression estimating the effects of local dial adoption on (log) employment in select occupations in the telephone industry. The table provides results estimated using the estimation method of Callaway and Sant'Anna (2021). *, **, *** represent significance at the 0.1, 0.05, and 0.01 levels, respectively. SEs clustered by city in parentheses.

Table D.4: Changes in the operating force and managerial employment

Panel A: Composition of telephone operators

	Ln(Fem. operators)			
	(1)	(2)	(3)	(4)
	Age 16-25	Age 26+	Average age	Share 26+
Post-cutover	-0.515***	-0.265***	1.469***	0.062***
	(0.050)	(0.043)	(0.251)	(0.014)
N	10852	10852	10577	10577
Y mean	1.782	1.345	25.822	0.375

Panel B: Managerial employment

	(1)	(2)	(3)	(4)
	Managers	Inspectors	All workers	Wrkrs:Mgrs
Post-cutover	0.099**	0.087**	-0.176***	-13.654***
	(0.048)	(0.037)	(0.039)	(4.412)
N	10852	10852	10852	4931
Y mean	0.489	0.085	2.785	22.182

Notes: Table presents results from a DID regression estimating the effects of local dial adoption on the composition of the telephone operating force (Panel A) and employment in managerial and quality control occupations (Panel B), including managers and service inspectors. The table provides results estimated using the estimation method of Callaway and Sant'Anna (2021). *, **, *** represent significance at the 0.1, 0.05, and 0.01 levels, respectively. SEs clustered by city in parentheses.

D.2 Related results from Feigenbaum and Gross (2022)

Below we take an event study approach to evaluating the relationship between cutovers and young women's employment, reproducing a subset of the results of our concurrent writing in Feigenbaum and Gross (2022). We focus on cities with population ≤100,000 in 1920, which were typically cut over to dial all at once. Using our decadal city panel, we estimate changes in the fraction of young women employed as telephone operators and in the telephone industry, and the fraction working at all, prior to a city's first 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} include state-year fixed effects and city population controls, to account for differential trends across larger and smaller cities. 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.5, Panel (A) shows that young women's employment in telephone operation was growing rapidly in the run-up to cutovers, up 0.8 p.p. in the decade just before mechanization on an average base of 3.2 p.p. of group employment, a 25% 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 36+). Older operators typically worked long-distance switchboards, which were not mechanized until after 1940. Here we find no such patterns.

Table D.5: Patterns of employment for select subpopulations in run-up to automation

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

	Pct. who are		Pct. who are operators		Pct. with
	tel. operators	in tel. industry	in tel. industry	in oth. industry	occupation
Years -20 to -10	0.469***	0.531***	0.442***	0.027	0.872
	(0.123)	(0.137)	(0.119)	(0.017)	(0.680)
Years -10 to 0	0.783***	0.920***	0.751***	0.032	1.352
	(0.161)	(0.171)	(0.151)	(0.028)	(0.858)
N	11645	11645	11645	11645	11656
R^2	0.65	0.67	0.65	0.47	0.86
Y mean	3.19	3.48	3.01	0.19	40.24

Panel (B): Older, white, American-born women (age 36+)

	Pct. who are		Pct. who are operators		Pct. with
	tel. operators	in tel. industry	in tel. industry	in oth. industry	occupation
Years -20 to -10	-0.047	-0.049	-0.056	0.008	0.659
	(0.041)	(0.048)	(0.037)	(0.012)	(0.431)
Years -10 to 0	-0.044	-0.059	-0.077	0.033	0.696
	(0.058)	(0.059)	(0.048)	(0.024)	(0.505)
N	11634	11634	11634	11634	11652
R^2	0.63	0.60	0.60	0.56	0.79
Y mean	0.85	0.90	0.72	0.13	19.50

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. Dependent variables are in units of percentage points (0 to 100) for legibility. The underlying sample spans 1910 to 1940 and is restricted to cities with population ≤100k in 1920. *, **, *** represent significance at the 0.1, 0.05, and 0.01 levels, respectively. SEs clustered by city in parentheses.

Appendix references

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