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Organizational and Economic Obstacles to Automation: A Cautionary Tale from AT&T in the Twentieth Century

James Feigenbaum,[a,b] Daniel P. Gross[b,c,*]

[a] Department of Economics, Boston University, Boston, Massachusetts 02215; [b] National Bureau of Economic Research, Cambridge, MA 02138; [c] Fuqua School of Business, Duke University, Durham, North Carolina 27708

*Corresponding author

Contact: jamesf@bu.edu, https://orcid.org/0000-0002-1625-2021 (JF); daniel.gross@duke.edu, https://orcid.org/0000-0001-8865-9835 (DPG)

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Abstract. AT&T was the largest U.S. firm for most of the 20th century. Telephone operators once comprised more than 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 that 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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1. Introduction

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 specter that "in a few years, [telephone] service will be thoroughly and completely mechanized" (Sullivan 1940, p. 16688). 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 (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 experience 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.

Although 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: the mechanization of call switching required 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 (Puranam and Raveendran 2013). We argue that the more interconnected a task is in its production environment, the more difficult its automation is 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 (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. However, once it recognized the necessary technical and organizational 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 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 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 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 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 (Henderson and Clark 1990; Milgrom and Roberts 1990, 1995). 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 (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 (although not necessarily limited to) the organizational and economic factors we emphasize in this paper.

Throughout the paper, we discuss myriad settings where automation is challenged by interdependencies. 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 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 2 provides a conceptual foundation for the paper. Section 3 reviews the history of AT&T, the U.S. telephone industry, and the development of mechanical switching. Section 4 discusses AT&T's reasons for and obstacles to automating telephone operation, emphasizing organizational factors, and Section 5 gives these ideas structure with a simple model. Section 6 presents evidence of organizational changes accompanying mechanical switching in local markets. In Section 7, we suggest an explanation for the long residual lags in diffusion once automation began. Section 8 discusses the generality of this example and concludes.

2. 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 20th 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 other 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 spillovers from their efforts.

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 (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 takeoff 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-20th 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).

2.1. 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 (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 economic 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 that interact, and the value of congruence may constrain investment choices.

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 versus 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 (through additional innovation), keeping existing interdependencies in place—not just the firm to the technology. As we will show, AT&T's technology and business developed jointly.

2.2. Connections to Organizational Design

Our work is thus closely related to the extensive literature on interdependence in organizational design (Puranam and Raveendran 2013, Raveendran et al. 2020)—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 (Baldwin and Clark 2000; Rivkin and Siggelkow 2003, 2007; Ethiraj and Levinthal 2004; Zhou 2013).[2] A second is the potential importance of aligning product and firm architectures (Sanchez and Mahoney 1996, Langlois 2002). A third is that internal dependencies can create obstacles to organizational change, including organizational adaptation to environmental change (Hannan and Freeman 1984, Levinthal 1997).

Technological change is one of many varieties of environmental change that cannot 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 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 that have thus far only been loosely connected.

3. 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 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 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 roughly two dozen 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 that 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, and a settlement in 1913 effectively made AT&T a regulated monopoly, with interstate service regulated initially by the Interstate Commerce Commission and later the Federal Communications Commission, and local service regulated by state utility commissions.

The functional units of each operating company were individual telephone exchanges, which were 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 each call 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.

3.1. Structure of the Telephone Network

Online 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 United States, but by 1909, it had exchanges throughout the United States, 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 (Online 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. They also supported private branch exchange 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, 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).

3.1.1. Functions of the "Central Office".

Although 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 principal departments. The Traffic department was responsible for operating the switchboards—in other words, directing traffic. The Plant department installed and maintained telephone equipment at the exchange and in the area it served. The Commercial department took new orders and requests for service changes, prepared bills, and collected payments. The Accounting department kept financial records. Each exchange also had its own management and business office (NLRB 1944).

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.

3.2. Development of Mechanical Switching

The first mechanical switching system was invented by Almon Strowger, an undertaker in Kansas City in 1889.[5] This system evolved to be used with rotary dial telephone sets, where each turn of the dial transmitted an electrical pulse which actuated 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 that 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, p. 2).

As Freeman (1937, p. 3) 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,

Table 1. Characteristics of U.S. Telephone Industry, 1902–1937

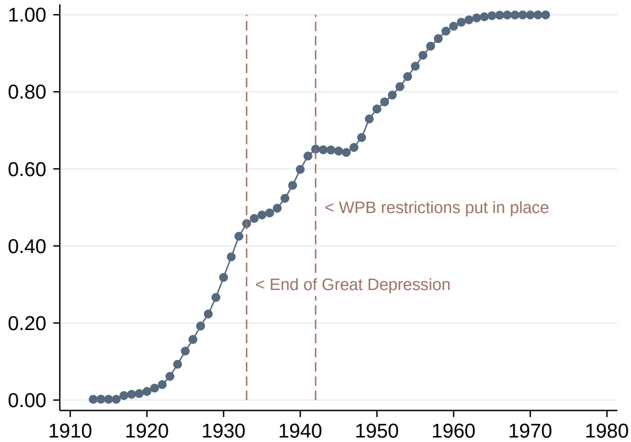
	1902	1907	1912	1917	1922	1927	1932	1937
Growth of industry								
Miles of wire (1000 s)	4,900	12,999	20,248	28,827	37,266	63,836	87,678	90,831
Telephones (1000 s)	2,371	6,119	8,730	11,717	14,347	18,523	17,424	19,453
Telephone calls (MMs)	5,071	11,373	13,736	21,846	24,648	31,614	30,048	33,618
Telephone 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 >$5,000 in income (1912 dollars) and thus slightly understated.

multiexchange cities, backing this recommendation with evaluations of relative connection speeds, accuracy, cost, versatility, customer sentiment, and the severity of the "labor problem" (Gherardi 1917, p. 4). 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. However, 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

Figure 1. (Color online) Percent of Bell System on Dial, 1913–1972



Notes. 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.

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 it appears 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 20 times in miles of wire, 10 times in number of telephones, 6 times in number of calls, and 5 times in employment. By 1932, AT&T served nearly 80% of all telephones in the United States (even more in urban markets). Figure 1 shows the diffusion of dial within the Bell System, which reached 32% by 1930 and 60% by 1940—but ultimately extends into the 1970s.

4. 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, p. 14).

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 (because 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, because 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 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 that operator wages were being driven higher, allegedly by labor market competition—although 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).

4.1. Organizational Barriers

Not all 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 principal 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 2 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.

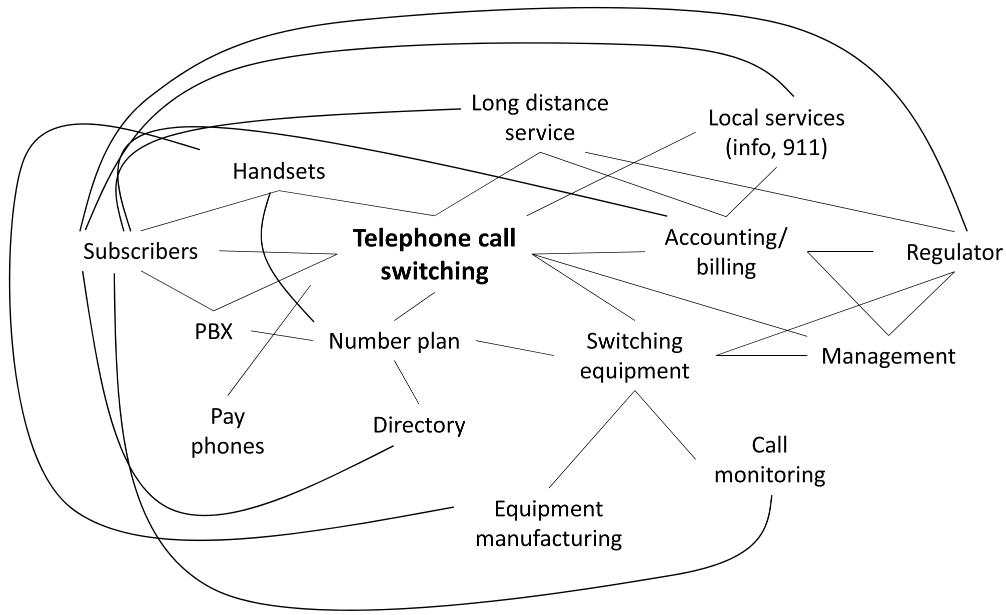
Figure 2 depicts interdependence across AT&T's business but illustrates that call switching is the most interconnected component of the system. Call switching's centrality in this web of activities makes it our canonical example of an "integral task." Its embeddedness meant that significant changes in 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, p. 328) 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 semimechanical 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 2 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 rewire the exchange. At times, this required constructing entire new buildings and physically relocating 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.

Figure 2. Integrating Automation into the AT&T Production System

(a)



(b)

<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

Notes. (a) Example interdependencies in the AT&T system. (b) Major activities and changes required to adapt this system to mechanical switching.

Mechanical switching required new handsets, new telephone numbers, and the issuance of new telephone directories. One of the most important but subtle, nonobvious 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 multiexchange cities were identified by an exchange name plus a four-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 three-character prefix using the same 10 numeric slots that 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. User education took place through media campaigns—including 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.

4.2. 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 (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. However, 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. The crucial sources of interdependence seem to have been between call switching and other parts of the business.

4.3. 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 AT&T was slow to use it.[8] With experience, AT&T 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.

5. Model of Interdependence

To provide a more structured understanding as 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 Online Appendix B.

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 will give structure to later.

This firm has a task-based production function. Each unit of output requires performing activities $i = 1, \ldots, n$, 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 raw inputs are incrementally converted to output across successive stages; or a complex activity system like that shown in Figure 2.[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, which is an aggregation of the cost of activities $i = 1, \ldots, n$, 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 $c = (\sum_{i=1}^{n} g(i))n$. 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. 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 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 first solve for equilibrium P^*, Q^*, and π^*, conditional on c, and then 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 Online 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 as given, and selects 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 proceed to evaluate the four scenarios, spanning from zero to partial to complete automation (Table 2).

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 $M > \max\{a(1 - \frac{1}{2}\alpha)n^2, a(1-\beta)n^2\}$, which ensures production can profitably occur in all automation conditions.

Table 2. Automation Scenarios: None, Partial, and Complete

	Parameters			
Scenario	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 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*

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

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

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 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—that is, 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.*

Although partial automation may be ruled out by the high value of congruence, complete automation may still be a possibility because 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 $\frac{1}{2}\alpha$ (versus 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.

6. 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. Although many of the adjustments we described in Section 4—such as price changes, building design, numbering systems, and so on—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 data set of local cutovers to mechanical switching across the United States 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 more than 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' earliest cutover. As we document in Online Appendix C, the majority of these cities were sufficiently small that the entire population was cut over to dial in one discrete event.

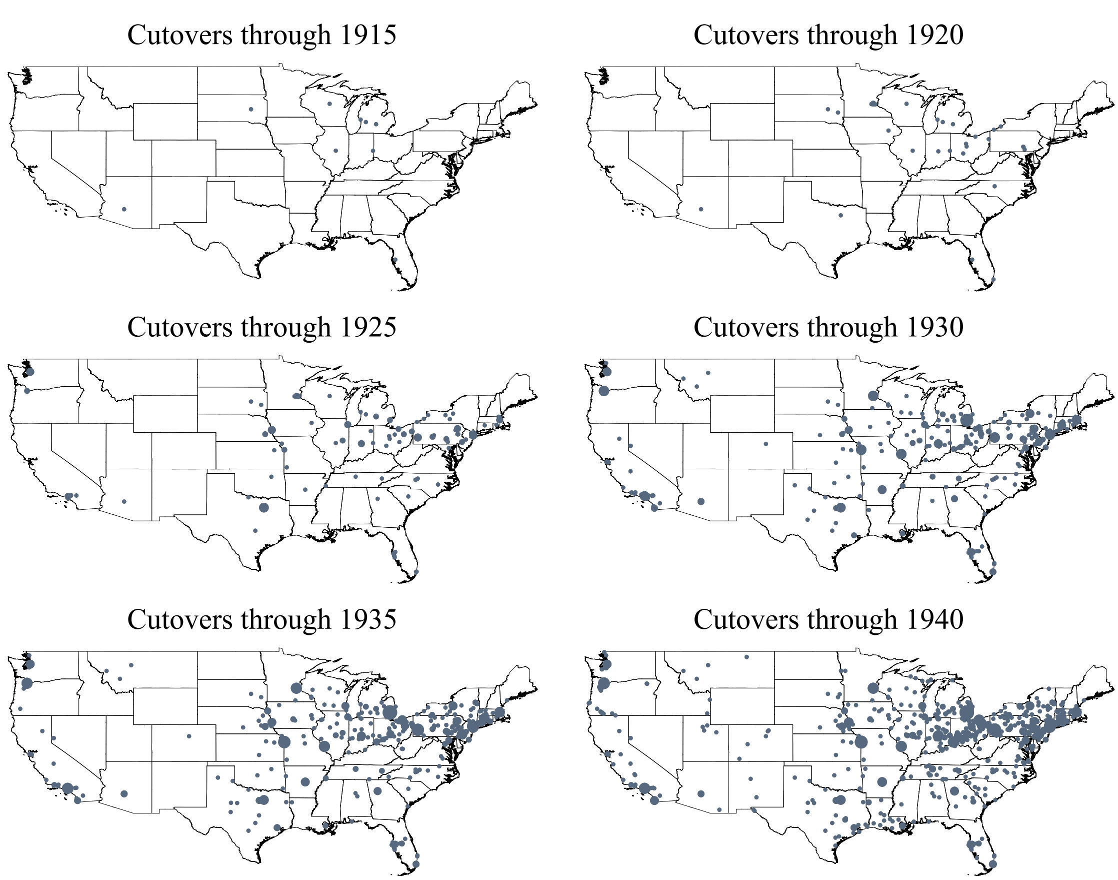
We merge these data with IPUMS complete count U.S. census data for 1910 to 1940 (Ruggles et al. 2019), which provide individual-level information on the entire U.S. population, including geographic, demographic, and occupational characteristics. We first undertake an effort to harmonize city names in the census data (Online 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 3 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 that were on dial at the end of 1939.

6.1. Automation-Driven Changes in AT&T's Workforce

Table 3 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

Figure 3. (Color online) Cities with Cutovers in Newspapers Data, in 5-Year Intervals, 1915–1940



Notes. 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.

Table 3. Principal Occupations in the Telephone Industry, 1910–1940

	1910		1920		1930		1940		
Occupation	Rank	Percent	Rank	Percent	Rank	Percent	Rank	Percent	Percent 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 16–65) in each census who live populated cities (as we measure them; see Section 6) and report working in the telephone industry. Sample excludes workers with unknown occupations. The table also reports the share of telephone industry workers in each occupation that are women.

classification (Online Appendix Figure A.4), which identifies these titles among its occupational classes.

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 two-way fixed effects 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 which converted to dial all at once (whereas large cities were converted in a more piecemeal fashion—a pattern evidenced in Online 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]

We estimate the following specification:

$$Y_{it} = \beta \cdot \mathbb{1}(\text{Post-cutover}_{it}) + \alpha_i + \delta_t + X_{it}\phi + \varepsilon_{it}, \quad (1)$$

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 7. As an empirical matter, we find that this control can eliminate differential pretrends across the outcomes we study.

Table 4 reports the effects of cutovers on telephone industry employment in several occupations that might have 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 the automatic equipment required. The most telling evidence that

Table 4. Effects of Dial on the Occupational Structure of the Telephone Industry

	Ln(Female...)			Ln(Male...)			
	(1) Operators	(2) Clerks	(3) Bookkeepers	(4) Electricians	(5) Electric engineers	(6) Mechanics	(7) Linemen
Postcutover	−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	10,852	10,852	10,852	10,852	10,852	10,852	10,852
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 two-way fixed effects regression estimating the effects of local dial adoption on (log) employment in select occupations in the telephone industry. Standard errors clustered by city in parentheses.
$^*p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

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 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.

In Table 5, 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 in the older age group (column 4) increased after cutovers. This compositional change is consistent with the remaining call switching tasks being 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 a low base; columns 1 and 2). Coupled with an overall 26% 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—because supervisory operators could oversee a complete row of junior operators, and chief operators managed the entire operating staff (see Online Appendix Figure A.3).

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, can potentially be 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 4 but are more difficult to systematically measure. In Online Appendix D, we also establish the robustness of these results to other two-way fixed effects estimation methods suggested in recent research (Callaway and Sant'Anna 2021, Borusyak et al. 2024).[16]

7. Long Tail of Diffusion

Developing mechanical switching technology, and designing a new business model around it, ostensibly

Table 5. Changes in the Operating Force and Managerial Employment

Panel A: Composition of telephone operators				
	Ln(Female operators)			
	(1) Age 16–25	(2) Age 26+	(3) Average age	(4) Share 26+
Postcutover	−0.536***	−0.326***	1.552***	0.061***
	(0.042)	(0.038)	(0.290)	(0.015)
N	10,852	10,852	10,580	10,580
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) Managers	(2) Inspectors	(3) All workers	(4) Workers:managers
Postcutover	0.088**	0.053**	−0.262***	−12.802***
	(0.036)	(0.024)	(0.027)	(2.515)
N	10,852	10,852	10,852	4,986
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 two-way fixed effects 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. Standard errors clustered by city in parentheses.
*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

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 6 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.

7.1. 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 6 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 in the table as 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.

In Table 7, we evaluate these patterns in a multivariate context. We estimate the following cross-city regression while controlling for state fixed effects (α_s):

$$Y_i = X_i\beta + \alpha_s + \varepsilon_i, \qquad (2)$$

where i indexes cities, and Y_i measures whether a city has a pre-1940 cutover (columns 1 and 2) or the year of its first cutover (columns 3 and 4), and X_i includes the city characteristics in Table 6. 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, although 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 7 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 Online 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, although 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 facing a limited supply.

7.2. Explaining the Long Tail

The patterns in Tables 6 and 7 connect closely to our theoretical structure in Section 5. 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 5, 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 $FC = (1 + n)\theta$

Table 6. 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+ (1000 s)	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	2,660

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 7. 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	2,991	2,991	324	324
R^2	0.24	0.24	0.28	0.28
Y Mean	0.11	0.11	1,929.08	1,929.08

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 1–2), and the timing of the earliest cutover (columns 3–4) 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). All specifications include state fixed effects. Robust standard errors in parentheses.
*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

to implement. If total costs $FC + VC = (1+n)\theta + c'Q < cQ$, then automation is a profitable investment. We can immediately see that 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 that subscriber creates. Total variable cost savings 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 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 5 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 $\alpha(t) = (1-\beta)\cdot(1-\exp^{-t})$, which is growing over time at time $t = 0$ it has zero impact and at the limit generates savings of $1-\beta$, reducing marginal costs to zero because ($c'(t) = (1 - \alpha(t) - \beta)n^2$). Even if c' were linear in t, it would take 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 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 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 vs. 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.

8. 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 AT&T may seem to be a distinctive case. In many ways it is: AT&T was the largest U.S. employer for most of the 20th 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. With increasing concentration in product and labor markets today, especially among high-tech firms in complex, networked industries, understanding what causes and challenges automation in these settings and what impacts it might have is valuable. If nothing else, we believe AT&T's sheer size and outsized role in business and economic history make it intrinsically important.

Two hesitations may 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 these countries had different commercial and regulatory environments from the United States (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 A, 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 would thus benefit from eliminating 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 healthcare, 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, and the degree to which automation reinforces winner-take-all industry dynamics. We believe these questions are ripe for further attention, and 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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Endnotes

[1] The language used to describe organizational interdependence varies somewhat across this literature. Simon (1962), for example, compares "complex" versus "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.

[2] A corollary literature has also cautioned of bottlenecks at tasks that connect many others, such as those connecting otherwise-independent subsystems (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)—although these may often coincide, and telephone call switching seems to us to be an example of both.

[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).

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

[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).

[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, p. 11).

[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—although AT&T would have faced the same challenges even if its hiring pool were broader.

[8] Online 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 myriad challenges of adopting mechanical switching.

[9] As in Section 2, 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), although 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 the pooled, sequential, and reciprocal interdependence of Thompson (1967).

[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 $\beta > \frac{1}{2}\alpha$; that is, congruence is more valuable than task-level cost savings), or automation of the integral task (vice versa). See Online Appendix B for explanation.

[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 Online Appendix C for complete details of the data collection effort.

[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.

[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.

[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 the sample is treated. To a first order, we do not expect these threats to be problematic in our setting, because 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.

[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.

[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.

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