

A Penny for your Thoughts*

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Abstract

How do communication costs affect the production of new ideas and inventions? To answer this question, we study the introduction of the Uniform Penny Post in Great Britain in 1840. This reform replaced the previous system of expensive distance-based postage fees with a uniform low rate of one penny for sending letters anywhere in the country. The result was a large spatially-varied reduction in the cost of communicating across locations. We study the impact of this reform on the production of scientific knowledge using citation links constructed from a leading academic journal, the *Philosophical Transactions* and the impact on the development of new technology using patent data. Our results provide quantitative causal estimates showing how a fall in communication costs can increase the rate at which scientific knowledge is exchanged and new ideas and technologies are developed. This evidence lends direct empirical support to an extensive theoretical literature in economic growth and urban economics positing that more ideas can emerge from communication between individuals.

Keywords: Communication, Innovation, Knowledge Flows, Penny Black Stamp
JEL codes:

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1 Introduction

The exchange of knowledge and new ideas is central to many facets of economic activity. For example, the sustained increase in standards of living enjoyed by modern economies is often explained by the creation and diffusion of ideas (Romer, 1986; Lucas, 1988, 2009; Buera & Oberfield, 2020). Further, the costly nature of ideas exchange generates agglomeration forces that contribute to explain the existence of cities (Marshall, 1890; Duranton & Puga, 2004; Davis & Dingel, 2019).

The fundamental premise in these views is that new ideas are more likely to emerge when communication between individuals is less expensive. Although such a premise is natural, isolating the causal impact of communication costs on the circulation and creation of knowledge has proven challenging. This consideration is particularly true in modern environments, where individuals can exchange knowledge through a wide variety of close substitute channels, and many confounding factors limit the scope of the analysis.

In this paper, we empirically investigate the effect of communication costs on the creation of new ideas. To circumvent some of the challenges found in modern environments, we turn to the Great Britain of 1830s-1850s, a historical setting where letters, the primary form of long-distance communication, had few close substitute channels. In 1840, the introduction of the “Uniform Penny Post” ([Postage Act, 1839](#)) spurred a country-wide communication revolution. This reform, spearheaded by Rowland Hill, replaced an expensive system of distance-based postage with a single, low, uniform charge of one penny for a standard-sized letter. Because the post was the primary form of long-distance communication at this time, this reform had a major impact on communication costs. Also, since the new uniform charge replaced a distance-based postage system, this reduction was spatially varied. We leverage these features to estimate the impact of a change in communication costs on the exchange of scientific knowledge and the development of new ideas and technologies, outcomes of particular interest because of their role in economic growth.

To measure the impact of the reform on scientific progress, we focus on articles and citations in the leading British scientific journal of the period, the *Philosophical Transactions of the Royal Society of London*. The primary challenge in constructing this new outcome measure is identifying and geolocating both the article authors and those they cite. Geolocating these individuals requires manually searching for and reviewing biographical sources on each individual, an extremely labor-intensive process. Through this process we were able to identify and geolocate between 88 and 100 percent of article authors and those that they cite for each year from 1830-1849, providing a decade of observations on either side of the reform.

To study how citations between scientists were affected by the reduction in communication costs, we need to measure the change in postage costs for letters flowing between any pair of scientists. In order to do so, we digitized and geolocated a list of 618 post offices and over 1,600 sub-post offices operating in England, Wales or Scotland just before the reform, and the postal road network through which each post

office connected to the others. Each scientist is then matched to the nearest post office, either directly or through a sub-post office, allowing us to calculate the change in postage costs between each pair of post office locations induced by the reform.

A key feature of this “citation dataset” is that the citations reflect bilateral flows of knowledge inputs. This allows us to adopt standard analysis methods from the trade literature which estimate the impact of a reduction in trade costs (or in our case communication costs) on flows while controlling for origin-time, destination-time, and location-pair fixed effects. Using this method, we find evidence of a substantial increase in citations between scientist pairs that experienced a greater reduction in communication costs as a result of the postal reform. Specifically, our results indicate that the introduction of the Uniform Penny Post eliminated between two-thirds and three-quarters of the decay of citations associated to distance across locations. This provides a first piece of evidence on the impact of communication costs on scientific knowledge flows.

To complement our evidence on knowledge flows between scientists, in the second part of the analysis we examine the impact of the reduction in communication costs on the development of new patented technologies. This outcome reflects a second dimension through which communication costs may have affected the development of new ideas, and one that is of particular importance for economic growth over the short to medium term. To conduct this analysis, we geolocated all addresses reported in the thousands of patents filed between 1830 and 1849. There is one important difference between our patent data analysis approach and what we do with the citation data. Unlike the citation dataset, our patent dataset reflects location-level outcomes, rather than bilateral flows, so it does not admit the analysis approach that is possible with the citation data.¹ Because patents are a location-level outcome, we need to construct a location-level measure of treatment due to the reform. To do so, we follow the market access approach of ([Donaldson & Hornbeck, 2016](#)), but with two important differences. First, the cost of communication is determined by postage rates. Second, these rates are based on the length of the postal routes which mail carriers followed at the time. Naturally, this “letter market access” measure is related to a location’s market access, so our preferred patent data analysis specification includes a standard market access measure, calculated over the joint waterways, rail and road network, as a control.

To implement this research design, we need to estimate the increase in towns’ letter market access caused by the reform, for which elasticities of letter flows to distance, cost and population are needed. We recover these elasticities using data on letters sent to London from hundreds of post towns during one week in 1838. We use an iterative procedure to circumvent the absence of a full matrix of letter flows. This preliminary step also provides direct evidence that postal costs had a large impact on the volume of letter flows.

Using a simple difference-in-difference analysis strategy, our patent data analysis shows that locations that experienced a greater increase in letter market access produced more patents after the postage reform, controlling for each location’s market access as well as other potentially important confounders, such as

¹Patent citations are not available in the setting that we study.

the location's own population and county-by-decade patenting trends. Our results are robust to a variety of estimation approaches. Our patent data analysis provides a second complementary and consistent piece of evidence on the impact of the fall in communication costs on the exchange of scientific knowledge and the production of new ideas.

By providing direct evidence on the influence of communication costs on science and innovation, our results contribute direct empirical support to the link between communication among individuals and the diffusion and creation of new ideas. This link is at the core of a large literature in economic growth (Romer, 1986; Lucas, 1988, 2009; Buera & Oberfield, 2020) and urban economics (Marshall, 1890; Duranton & Puga, 2004; Davis & Dingel, 2019).

Our results fill in a missing piece between several existing strands of work. On the one hand, there are a number of studies that focus on isolating the impact of communication costs or communication disruptions on other economic outcomes, including Jensen (2007), Goyal (2010), Aker (2010), Allen (2014), Koudijs (2014), and Steinwender (2018). Our study differs from this work in that we focus on the impact of changing communication costs on scientific knowledge and technology development, two outcomes that are of particular importance for economic growth.

Our study is also related to existing work looking at how changes in trade costs influence innovation rates. Agrawal *et al.* (2017), for example, estimates the impact of highways on innovation, while Catalini *et al.* (2020) studies the impact of a fall in airfares. An important distinction between work in this area and our study is that changes in highways or air transport can affect both the cost of transporting goods (or people) as well as the cost of communication. A novel feature of our study is our ability to isolate the impact of changes in communication costs from the effect of broader changes in transport costs.

Another related strand of research uses patent data or academic citations to infer the existence of knowledge flows related to science or invention (Jaffe *et al.*, 1993; Thompson, 2006; Murata *et al.*, 2014). Existing evidence suggests that communication costs likely play an important role in inventive activity. However, it is difficult to establish a direct causal relationship using these methods because studies in this area typically do not observe plausibly exogenous changes in communication costs, and because increased communication via one channel may in part reflect reduced communication via the many alternative, close substitute channels.² This makes it hard to isolate the role of communication from other omitted local factors, as well as other impacts of proximity such as reduced transport costs.

A particularly productive strand of work focuses on academic research, where some of the identification issues faced by studies of the broader economy can be overcome. For example, Waldinger (2011) uses the expulsion of scientists by the Nazis to provide evidence on localized peer effects. Another paper that is even closer to our study is Agrawal & Goldfarb (2008). In that paper the authors examine the impact of a very specific reduction in communication costs between universities – the adoption of Bitnet, a precursor of the Internet – on inter-university collaboration in engineering. Their results indicate that the reduction

²Additional evidence shows that inventive activity tends to be geographically agglomerated, and more so than manufacturing activities in the same industry (Audretsch & Feldman, 1996; Carlino *et al.*, 2012).

in communication costs increased collaboration between university researchers.³ There are two important differences between our study and [Agrawal & Goldfarb \(2008\)](#). First, our citation data analysis takes advantage of information on bilateral knowledge flows (citations) and bilateral variation in the change in communication costs, which allows an analysis approach that addresses many potential identification concerns. Second, our evidence on the impact of reduced communication costs on scientific knowledge is complemented by our evidence on the development of new technologies, which are likely to be particularly important for improving economic growth.

Our study also contributes to existing work looking at the impact of postal systems on economic development. One closely related study, [Acemoglu *et al.* \(2016\)](#), uses the presence of post offices as an indicator of state capacity and then shows that this measure is correlated with subsequent patenting activity. While these results suggest a link between the presence of post offices and innovative output, they do not attempt to isolate the importance of communication costs from other aspects of state capacity. Another closely related paper, [Rogowski *et al.* \(2019\)](#), uses a combination of cross-national and U.S. county-level data on the extension of the postal system and finds that greater access to the postal system was associated with faster development (as indicated by national GDP or county level farm values, manufacturing output or capital investment). Relative to [Acemoglu *et al.* \(2016\)](#), our study provide more direct causal estimates of the impact of reduced communication costs, through the postal system, on innovation. Relative to [Rogowski *et al.* \(2019\)](#), we offer both a more cleanly identified analysis approach as well as evidence on how communication costs affected scientific and technology development, rather than broader economic development.⁴

Finally, our paper improves our understanding of a key event in British economic history. The introduction of the penny post provides a particularly interesting example of how an institutional reform can contribute to sustaining technological progress and economic growth: economic historians such as Joel Mokyr have argued that knowledge exchange played a critical role in facilitating technological development during the Industrial Revolution ([Mokyr, 2005a](#)). That the reform of this particular institution mattered should not be surprising, given that during the nineteenth century the post office was almost certainly the branch of national government that individuals were most likely to encounter in their everyday lives.⁵

The rest of the paper is organized as follows. Section 2 provides background information on the postal reform. We present our data in Section 3. This is followed by Section 4 that establishes the relationship between of postage costs and the volume of letter flows. Our main analysis is in Section 5, followed by a concluding discussion.

³Other recent studies in this area include [Belenzon & Schankerman \(2013\)](#) and [Boudreau *et al.* \(2017\)](#).

⁴Another working paper, by [Feigenbaum & Rotemberg \(2014\)](#), also looks at the impact of postal access, using the expansion of postal services in the United States through rural free delivery. They find that this expansion impacted production patterns, but they do not study the impact on innovation.

⁵For an eloquent exposition of this point, see [Acemoglu *et al.* \(2016\)](#).

2 Background

In the early nineteenth century, posting letters was the primary means of long-distance communication. Scientists, engineers, and other inventors were often heavy users of the postal system. The surviving correspondence of Michael Faraday, for example, a prominent English scientist working on electromagnetism, comprises over 4,900 letters ([James, 1991-2011](#)). So important and voluminous were these correspondences that in many cases they provide the primary record that we have of the lives of scientists and inventors during this period. Letters exchanged between scientists and inventors were often packed with scientific knowledge, technical information, and questions. As the optical scientist and photographic inventor David Brewster wrote to William Henry Fox Talbot in 1837, “My last letter was so crammed with Science, that I could not find a corner to ask your aid in a question of Literature...” ([Schaaf, 2021](#)).

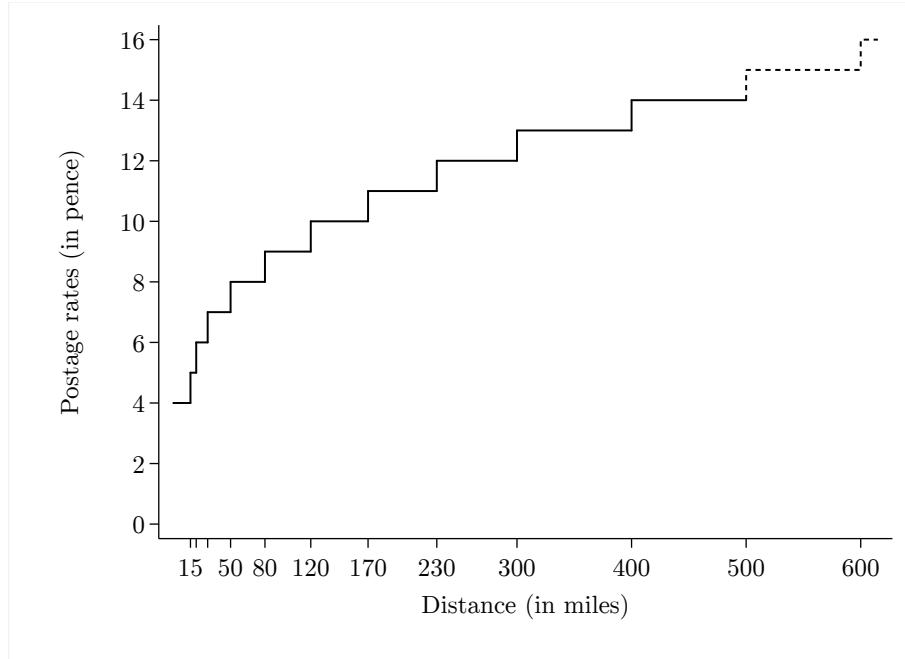
However, in the 1830s there was a great deal of dissatisfaction with the postage system in Britain. This was due in part to the fact that, prior to 1840, one of the primary aims of the Post Office was to raise revenue for the government through the use of its monopoly power. Reflecting this aim, postal rates had been repeatedly raised in the early nineteenth century in response to the revenue needs created by the Napoleonic Wars.⁶ Not only were costs high, but the system of distance-based rates was complex. Postage was based on the carrier’s journey, the cost was dependent on weight and the number of sheets, and the postage was typically paid by the recipient. The postage varied discretely at specific distance thresholds, with wider bands for longer distances. Figure 1 shows the cost function as reconstructed from original documents. This all added to the expense of sending a letter. High expenses also meant lower letter flows, which resulted in less frequent deliveries.

In the late 1830s, Rowland Hill became a leading advocate of post office reform. In 1837, he published his famous pamphlet, *Post Office Reform, its Importance and Practicability*, in which he argued for the introduction of a flat postage rate independent of distance for all letters up to 14 grams, and the introduction of prepaid postage indicated by a stamp on the letter.⁷ Hill argued that reducing postage rates would actually increase revenues, because the quantity of letters sent would offset the lower price per letter, while at the same time simplifying the system could also allow the Post Office to handle more

⁶MPs and other high-level government officials were exempt from paying for postage because they had what were called “franking privileges” that allowed them to send ten and receive 15 letters per day at no cost ([Postage Act, 1795](#)). These individuals were also known to post letters for some friends. The Postage Act of 1839 ended these franking privileges and introduced uniform one-penny postage for everyone. Non-commissioned officers in the Royal Navy and Royal Army already benefited from this low uniform rate before the reform. In our analysis below, the presence of these privileges will reduce the impact of treatment, since anyone with franking privileges and any non-commissioned officer in the military will not be treated by our reform. This will have the effect of pushing our estimated treatment effects toward zero, though we do not expect the effect to be very large. Thus, our results can be thought of as a lower bound on the impact of the reform had it applied equally to everyone in the country.

⁷Much earlier, in 1680, William Dockwra and his partner Robert Murray established the London Penny Post which was, however, restricted to postings within London. Other local penny posts existed within other parts of the country and exclusively served the local communities within their small coverage areas. The reform we study was focused on inter-city postage, a feature reflected in our analysis.

Figure 1: Postage cost of a one-page letter, pre-reform



Note: This figure shows the postage cost for a one-page letter before the postal reform. The dashed line indicates that for every additional 100 miles an additional penny was being charged.

letters at a lower cost.

The pamphlet was less popular among Post Office officials who feared increasing costs, but a House of Commons Select Committee led by Robert Wallace, MP was favorable. The Committee reports 320 petitions containing 38,709 signatures in support of Hill's plan ([Wallace, 1837-38](#)). As a result, the Penny Postage Bill was passed in July 1839 and a uniform penny postage was officially launched on 10 January 1840.⁸ From this day on, "... a Letter not exceeding half an ounce in weight [could] be sent from any part of the United Kingdom, to any other part, for One Penny ..." ([General Post Office, 1840](#), p.1).⁹ Only five months later, the introduction of the *Penny Black* stamp, the first adhesive postage stamp worldwide, concluded Britain's transition to the first modern postal system.

The reform dramatically reduced the cost of long-distance postage, leading to a rapid increase in the volume of letters sent. The cost of sending a letter of three sheets from London to Edinburgh, for

⁸Some MPs were initially skeptical that Hill's plan would generate sufficient revenue and called for a higher uniform rate. The resulting Uniform Fourpenny Post launched on 5 December 1839, led to a volume increase of 28 percent within less than a month, convinced skeptics of the uniform penny rate, and quickly became the victim of its own success (see [Hill, 1840](#), [Coase, 1939](#)).

⁹In contrast to the pre-reform period, this weight limit meant that the lowest rate also applied to two-sheet letters.

example, dropped from 39 1/2 pence to 2 pence. This was a large decrease, even for the relatively well-off scientists and engineers in our sample: the decrease in the cost of a three-sheet letter sent from London to Edinburgh was equal to a decrease from around 10-20% of a professor's average daily wage to just 0.5-1%.¹⁰

From 1839 to 1840, the number of letters posted in Great Britain more than doubled, from 73 million to 151 million, and the volume reached 312 million by 1850 ([General Post Office, 1856](#), p.56). This dramatic increase can be seen in Figure 2, where we present estimates of letter flows that we have constructed.¹¹ Since few alternatives existed for long-distance communication, such increase in the volume of letters likely represents a net increase in communication flows within the country. In response to the rise in letters, the postal system expanded rapidly, from 4,028 post offices in 1840 to 11,235 in 1858 ([General Post Office, 1855](#), p.20; [General Post Office, 1859](#), p.7). Greater letter volume also facilitated an increase in the frequency of deliveries, which improved the convenience of using the post.¹² Thus, the reform triggered a communication revolution that allowed people across Britain to exchange ideas and access knowledge at low costs.

Contemporary sources indicate the benefits that those working in the scientific and technical spheres enjoyed from their improved ability to communicate cheaply across distant locations. John Henslow, a friend and mentor of Charles Darwin, wrote that "To the importance of the penny postage to those who cultivate science, I can bear most unequivocal testimony, as I am continually receiving and transmitting a variety of specimens by post. Among them, you will laugh to hear that I have received three living carnivorous slugs, which arrived safely in a pill-box!" ([Lewins, 1865](#), p.200). This quote nicely summarizes why we would expect this sudden decrease in communication costs to have a marked effect on science and technological progress.¹³

In addition to the postal reform that we study, there were other major changes in transportation that our study will have to deal with. By far the most important of these was the expansion of the railway, following the introduction of the first passenger railway between Liverpool and Manchester in 1830. We will be careful to control for the expansion of the railway system in our analysis. The telegraph was also introduced, starting in 1844, but initially this was used just as a signaling system for the railways so it is less of a concern for our study.¹⁴

¹⁰The calculation of the lower bound relies on [Colquhoun \(1806\)](#). For the upper bound, a salary of £300 per year is used based on a figure listed in the Oxford Dictionary of National Biography for a chaired professor at the University of Cambridge (see [Chapman, 2011](#)).

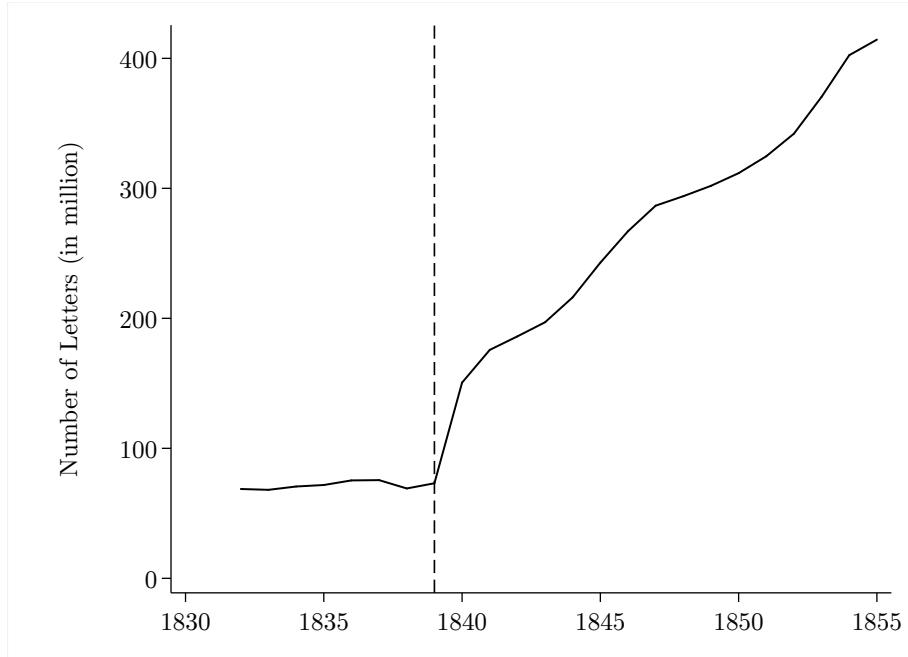
¹¹In Great Britain, the number of mailed letters per capita increased from about 4 in 1839 to about 17 in 1849. These estimates are obtained by dividing the letter flows for 1839 and 1849 by the 1841 and 1851 census population data.

¹²See [Select Committee on Postage \(1843\)](#) pp.258-261.

¹³The preserved individual correspondence of several scientists and the fact that one third of the male and half of the female population in Britain was still illiterate in 1840 suggest that scientists benefited disproportionately from the reform.

¹⁴The public initially made little use of the telegraph lines because of their limited availability and high cost ([Fava-Verde, 2018](#)). Only in the mid-1850s did the public begin using telegrams for private and business communication.

Figure 2: Letter volumes over time



3 Data

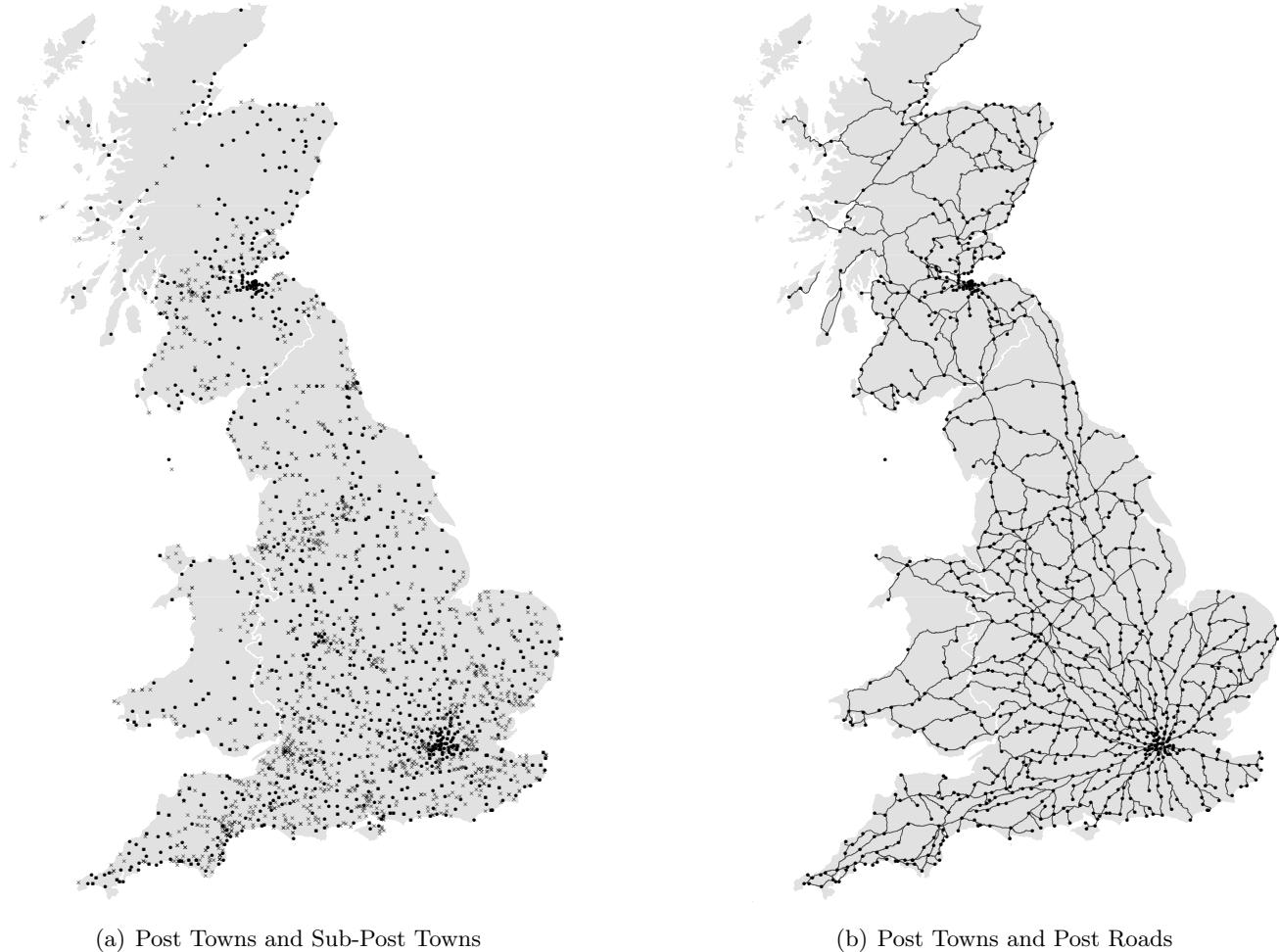
3.1 Measuring treatment

Because the reform we study lowered postage between any two points in the country to a low uniform rate, to measure the change in the postage rate due to the reform we simply need to estimate the rate in the pre-reform period. Because the pre-reform rate was distance-based, this requires that we construct the network of postal offices and post roads. Using original sources we have traced out the postal road network (which is not the same as the turnpike network, since not all roads were post roads) and connected them to a digitized and geocoded list of 618 post offices.¹⁵ Appendix C contains the details of this step. Figure 3 presents our digitized map of postal roads and post offices.

Essentially all of the large towns in England, Wales and Scotland had a post office, and most of the scientists and patentees that we study were located in one of these post towns. However, some were located in smaller towns, villages, or rural areas. To link these outlying patentees and scientists to our set of post towns, we have digitized and geolocated a more detailed list of over 1,600 sub-post offices, each

¹⁵See Select Committee on Postage, 1838, pp.153-165.

Figure 3: Post roads and post towns in Great Britain



Note: The maps show England, Wales and Scotland separated by white border lines. Panel (a) shows post towns (black dots) and sub-post towns (gray cross) observed around 1838. Panel (b) shows post towns (black dots) and postal roads digitized from maps around 1838.

of which is linked to a post office through which letters mailed at the sub-post office would have flowed. For scientists or patentees outside of the post towns, we link them to their nearest post or sub-post town and then to the main post town that their sub-post town was associated with.

The post towns will be our primary unit of analysis. Using the postal route network, we calculate the distance between every pair of post towns. We then use this distance together with the distance-based pricing scheme used in the pre-reform period documented above to calculate the bilateral cost of sending letters between locations before the reform. Since the reform lowered this cost to a low uniform rate, we

can use this pre-reform cost to compute the size of the cost reduction induced by the reform.

An important feature of the postage costs in the pre-reform period is that they were distance-based, but that this took the form of a step function. So, for example, to send a single-sheet letter fifteen miles in the pre-reform period cost 4 pence, but for distances from 15 to 20 miles the cost was 5 pence, for 20 to 30 miles it was 6 pence, and so on.¹⁶ At larger distances the bands were wider, so for distances from 80 to 120 miles the cost was 9 pence but the 10 pence band stretched from 120 to 170 miles. This structure, together with the fact that letters traveled along a specific set of postal routes, implies that the postal costs used to construct our key treatment variables are less correlated with bilateral distance. This binned cost structure is a useful feature for our analysis, particularly when we look at the patent data.

3.2 Measuring scientific knowledge flows

We measure scientific knowledge flows using articles published in the *Philosophical Transactions of the Royal Society of London*. First published in 1665, the *Philosophical Transactions* was the premier British scientific journal during our study period. A general-interest journal, it published articles across all branches of science.

Our analysis requires citation, location, and biographical data for all scientists who published or were cited in the *Philosophical Transactions* in the observation period.¹⁷ The citing practices in the first half of the 19th century necessarily differed from today's. Instead of citing specific publications, authors cited individual scientists and described the cited scientists' particular body of work that they used and built on in their articles, whether or not such work appeared in the *Philosophical Transactions*. The main reason for that is simple. The authors could not expect that readers had access to all publications. The citations in the *Philosophical Transactions* take the form of capitalized last names. Often, but not always, titles such as Prof., Dr., or Mr. are included. Authors typically introduced individuals when they could expect that readers would not be familiar with them.¹⁸ An example of a citation from a 1840 article in the *Philosophical Transactions* is reported in figure A1 in the Appendix.

To construct our data set, we began by collecting all of the 443 articles published in the journal from 1830-1849. We then disambiguate the authors of all articles using biographical information from the *Oxford Dictionary of National Biography*, the *Fellow Directory of the Royal Society*, and other similar sources. Finally, we use these sources as well as additional sources such as the 1841 census and city directories to find and record the modal geographic locations of all authors in the publication year(s) of their articles.

After identifying and geolocating all authors of the 443 articles, we limit our attention to the 389

¹⁶Letters with more pages faced higher rates but a similar step function increase in the cost at the same distance bands.

¹⁷Appendix E provides additional details on the data collection process and addresses co-authorship.

¹⁸These short introductions often described the relationship between the author and the cited individual or stated the cited individual's institution or location.

articles that were published by authors located in England, Wales, or Scotland.¹⁹ We then follow a systematic approach to identify and geolocate all scientists and inventors who are cited in this set of 389 articles. We record and geocode the modal locations of these cited individuals in the publication years of the corresponding articles.²⁰

Identifying the cited scientists solely based on their last names, titles, and the article content, in particular around the respective citation, provided for an extremely challenging and resource-intensive data collection.²¹ The geolocating process was even more labor-intensive than the identification and disambiguation process as it required an even more detailed review of available biographical information and the search and documentation of additional sources.²²

After uniquely identifying individuals, we find that our 389 articles include 2,611 citations to scientists who were living at the time the article was published. Out of this group, we were able to geolocate the cited scientists for 2,540 citations, 1,219 of which referred to a scientist living in England, Wales or Scotland, with at least 88 percent of citations geolocated in every year. Table B12 provides annual and period-specific summary statistics for all citations that we extracted from the 389 articles. The fact that we were able to identify and geolocate such a large fraction of scientists is due to the fact that most of them were reasonably prominent individuals for whom at least some surviving biographical information was available, as well as the very labor-intensive manual approach that we applied.

To provide a sense of the type of studies covered by our *Philosophical Transactions* data, we have categorized each article into one to three broad categories of scientific fields. Table 1 describes the distribution of articles across scientific fields. Clearly, our articles span a broad set of different scientific activities, ranging from basic science to more applied work. One take-away from this table is that many of the scientific topics covered in our citations data are focused on basic science topics, such as mathematics, or other topics, such as zoology, geology, or meteorology, that were unlikely to lead to patented inventions in the short run. Of course, this does not mean that such basic science was not valuable.

Direct correspondence through the post is one way that one scientist may have learned about the work of another. Other channels include reading about their work in scientific publications like the *Philosophical Transactions*, or correspondence through a third party. However, simply learning about existing work was only one step in the research process that led to a new scientific discovery. A review of the correspondence

¹⁹ Appendix E.1 provides additional information on both sets of articles. Summary statistics are available in tables B10 and B11.

²⁰The modal location in the publication year of the article may differ from the modal location at the time when the cited, sometimes unpublished work was produced, but going back in time to link scientists' particular bodies of work to their previous publications is infeasible. In any case, any error in this location measure due to this difference is unlikely to be correlated with treatment and so is unlikely to affect our estimates.

²¹We constructed an algorithm for identifying the cited scientists, instructed our research assistants how to use the algorithm, ensured that they followed the algorithm, frequently provided feedback to the research assistants, and conducted regular quality checks.

²²We provided our group of research assistants with detailed instructions on the location data entry and carefully checked the resulting data for accuracy.

Table 1: Topics in Philosophical Transactions, 1830-50

Topic	Share of articles	Share of pages	Topic	Share of articles	Share of pages
Medical	0.154	0.145	Geology	0.041	0.065
Meteorology	0.113	0.085	Mechanics/Physics	0.027	0.027
Magnetism	0.104	0.110	Botony	0.026	0.021
Electricity	0.092	0.099	Unclassifiable	0.017	0.032
Chemistry	0.092	0.080	Navigation	0.011	0.007
Zoology	0.078	0.081	Timekeeping	0.011	0.018
Geography	0.075	0.063	Archeology	0.010	0.009
Astronomy	0.059	0.077	Metallurgy	0.008	0.005
Light & Heat	0.055	0.057	Sound	0.006	0.005
Applied science	0.046	0.041	Demography	0.005	0.002
Mathematics	0.043	0.038	Units of measurement	0.004	0.004
Scientific Equipment	0.043	0.041			

undertaken by scientists during this period reveals that new discoveries were often preceded by extensive communication between scientists. So if cheaper postage facilitated the flow of communication, we would expect to see more articles with citations across longer distances in the post-reform period for two reasons. First, because it was easier for individuals to learn about the work of other scientists who were further away and second, because more frequent correspondence aided in the development of new ideas leading to a publication in the *Philosophical Transactions*.²³

3.3 Measuring the impact on technology development

A natural complement to our analysis of the sharing of more basic scientific knowledge is an analysis of the development of useful technologies. Both scientific knowledge and technological development are likely to make an important contribution to economic growth, though over different time horizons. These activities are also clearly related to one another, though there is an ongoing debate over how much basic science contributed to technological development during the Industrial Revolution.²⁴

²³It is worth noting that, in addition to analyzing bilateral citation data, it is in principle also possible for us to conduct a location-based analysis of the appearance of new scientific articles using the same methods that we will apply to the patent data. While this is possible in theory in our setting, in practice the relatively small number of articles published during our study period means that it is not feasible to obtain sufficient power for this type of analysis. Thus, we focus our attention on the richer information available in the bilateral citation data.

²⁴Contributions to this debate include Landes (1969), Rosenberg (1974), Mokyr (2002), Khan (2018), Jacob (2014), and Kelly & Ó Gráda (2020).

In order to study how the reduction in communication costs affected the development of new technology, we take advantage of patent data. Patent data provide a rich source of information for understanding technological development during our study period (and continuing on to today). Though patent data are not without their limitations (see, e.g., [MacLeod *et al.* \(2003\)](#) and [Moser \(2012\)](#)), their many advantages have led them to be widely used in studies seeking to understand patterns of technology development. In particular, patents provide a relatively rich set of information covering a large number of new technologies and they are subject to a set of clear and consistent (and in our study period, fairly stable) incentives.

One notable feature of our setting is that filing a patent was a very expensive process. [Sullivan \(1989\)](#) calculates that patent fees in 1830 were at least four times the average annual income. This very high cost likely reduced the number of low-quality patents filed during our study period, though it may mean that some useful technologies were never patented. As a consequence, we expect that our patent data include a select and generally higher-value subset of technologies developed during our study period.

For consistency with our citation analysis, our patent analysis focuses on the period from 1830-1849. Patent laws were stable during this period, though a major change in patent law did take place just after the end of our study period, in 1852.²⁵ It is useful to note that patents may have been increasing in attractiveness in the 1830s due to a set of court decisions that shifted the case law in favor of protecting patent holders ([Bottomley, 2014](#)). To the extent that this improved the attractiveness of filing a patent for inventors across all locations, this will be dealt with as part of our difference in difference analysis strategy.

The patent data that we use were compiled by the British Patent Office ([Woodcroft, 1854](#)) as part of the ‘Titles of Patents of Invention’. These data were digitized by [Nuvolari & Tartari \(2011\)](#), and we have geocoded them using a combination of the Google geocoding API and manual location searches.²⁶ We then link each patent to the nearest post town, either directly or through a closer sub-post town. The result is a list of 7,677 patents filed between 1830 and 1849, each assigned to a post town (our unit of analysis).²⁷ Appendix Figure A2 describes the number of patents in each year across the study period.

3.4 Travel Costs

We are interested in the effect of a decrease in communication costs on the creation of new ideas. One potential concern is that the emergence of the railway network during this time might bias the estimated effect of decreasing communication costs because it facilitated in-person communication (or other trade

²⁵For a comprehensive discussion, we refer the interested reader to a recent book by [Bottomley \(2014\)](#) as well as earlier work by [Dutton \(1984\)](#) and [MacLeod \(1988\)](#).

²⁶We are in debt to Alessandro Nuvolari for sharing the digitized list of patents with us. For a more detailed discussion of Woodcroft’s work, we refer the interested reader to [Nuvolari & Tartari \(2011\)](#).

²⁷For some patents in our database, the patent agent is listed in place of the inventor. Many of these were patents for inventions that were developed outside of the U.K. We have identified patent agents by reviewing personal biographies for those individuals with numerous patents. A number of these turn out to be patent agents. We exclude patents with patent agents listed as the inventor from our analysis.

flows). To disentangle the effect of in-person communication from postal communication, we calculate the minimum travel costs between all locations on a combined network of (i) coastal waterways; (ii) inland waterways and canals observed in 1830; (iii) turnpike roads observed in 1830; and newly added railway lines and stations for each year between 1830–1849.²⁸ Figure 4 shows two exemplary networks, one at the beginning of our time window in 1830 before the construction of the railway network and one at the end of our time window in 1849 when the backbone of the railway network had emerged.

To calculate travel costs, we connect the different transport networks at access points. Railway stations provide access to railway lines; ports provide access to coastal routes; and turnpike roads, navigable rivers and canals can be accessed anywhere. We further assume that travelling on water is 3 times more costly than travelling by rail and travelling on land is 4.5 times more costly than travelling by rail. These weights correspond to the weights estimated in [Donaldson \(2018\)](#) with 19th-century data. Using these cost parameters, we can calculate the minimum travel costs between all locations. This will allow us to control for the steady decline of in-person communication costs and focus on the abrupt change in postal communication costs, i.e. letter market access. The following section discusses our measure of letter market access in detail.

4 Postage costs and letter flows

Before analyzing the relationship between communication costs and knowledge flows, it is useful to establish the relationship between letter flows, distance, postage cost, and population. This analysis serves two purposes. First, it provides a key piece of evidence that communication costs were indeed strongly limiting communication flows. Second, our measure of location treatment in the patents analysis relies on estimates of the relation between letters, population, distance and cost that will be recovered in this exercise.

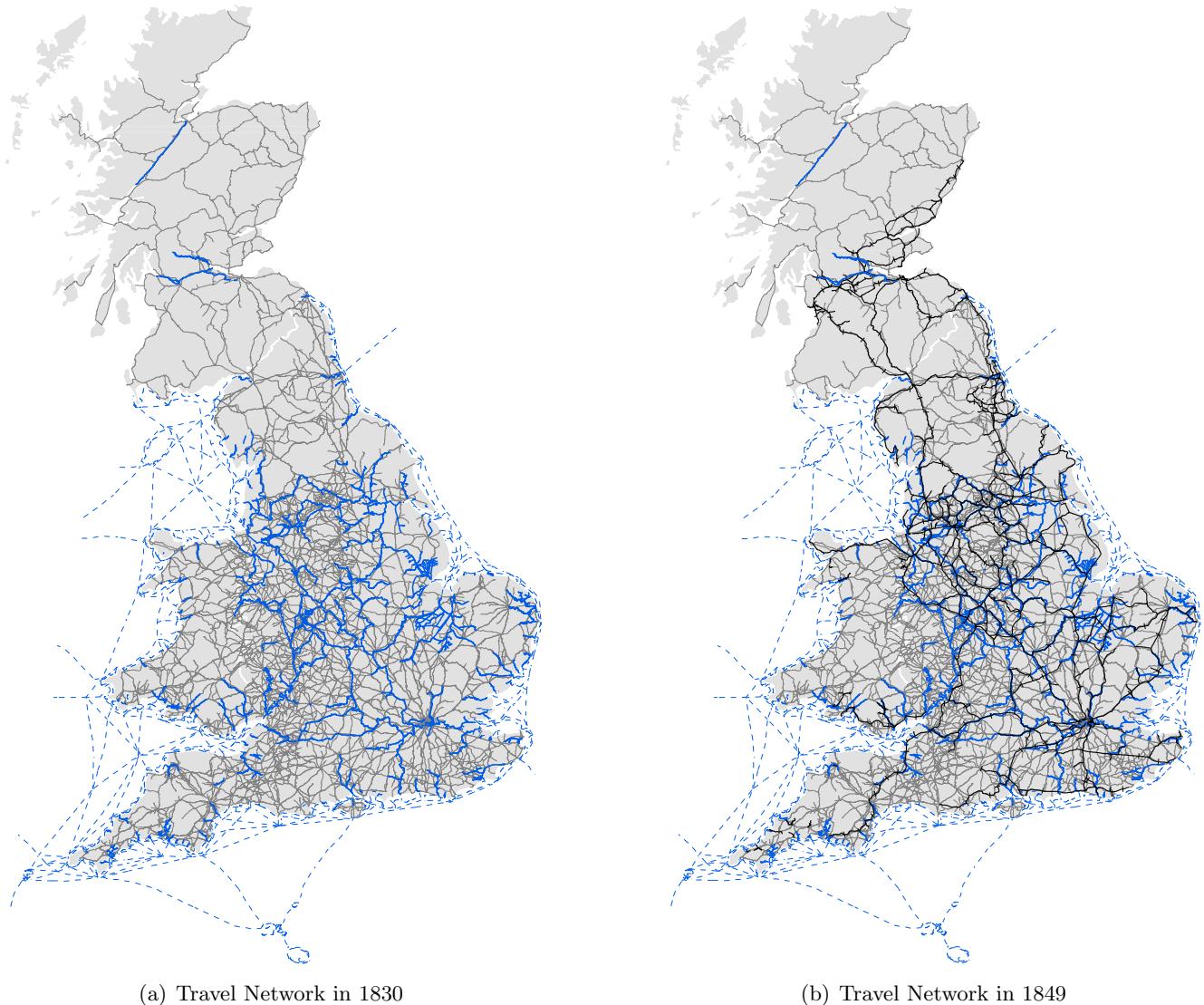
Let L_n be the total number of letters originating from location n . We posit that the flow of these letters sent to a location i follows a gravity specification of the form:

$$L_{ni} = \frac{A_i d_{ni}^{-\gamma} c_{ni}^{-\eta}}{\sum_{i' \neq n} A_{i'} d_{ni'}^{-\gamma} c_{ni'}^{-\eta}} L_n \quad (1)$$

In this expression, A_i is a parameter that captures the general propensity of location i to receive letters from anywhere; d_{ni} is the travel cost between locations n and i , which captures the fact that bilateral individual relationships are less likely to exist—and hence, bilateral letter flows are lower—when travel between two places is more expensive; c_{ni} is the monetary cost of sending letters from n to i ; and the

²⁸[Rosevear et al. \(2017\)](#) created a GIS of turnpike roads, [Satchell et al. \(2017\)](#) created a GIS of inland waterways, and [Alvarez-Palau et al. \(2019\)](#) created a GIS of ports. Railway lines were derived from a railway atlas by [Cobb \(2006\)](#). [Martí-Henneberg et al. \(2017\)](#) created the GIS of England, Wales and Scotland railway stations 1807-1994. See also [Bogart et al. \(2022\)](#).

Figure 4: Travel Network in 1830 and 1849



Note: The maps show England, Wales and Scotland separated by white border lines. Panel (a) shows coastal waterways (blue dashed line); 1830 inland waterways (blue line); and 1830 turnpike roads (gray cross). Panel (b) adds all railway lines built until 1849 to the map (black lines).

denominator captures the set of outside communication opportunities available to residents in n , which we can think of as a measure of *letter market access (LMA)*:

$$LMA_n = \sum_{i' \neq n} A_{i'} d_{ni'}^{-\gamma} c_{ni'}^{-\eta}. \quad (2)$$

The letter market access of an origin location grows with A_i and falls with travel and communication costs when $\gamma, \eta > 0$: hence, a larger LMA indicates that location n 's residents have a greater opportunity to communicate at cheap prices with places which tend to be more attractive communication destinations.

Note that communication within town ($i' = n$) is excluded from our measure of letter market access, which is a slight departure from the trade-inspired gravity equation for letters. We make this choice for three related reasons. First, personal interactions were a closer substitute for letters sent *within* a town but not over longer distances *between* towns. Second, historical evidence suggests that within-town communication was often used to convey short messages to *coordinate* personal interactions, rather than convey information *as a substitute for* personal interaction. Third, the type of information conveyed in letters is explicit, *codified* knowledge, whereas coordination for personal interactions facilitates the exchange of explicit as well as *tacit* knowledge. These three considerations imply that the gravity model we use for letter flows to London might not apply to distances that can be also covered by short individual travel: both the link between letter flows and our three explanatory variables, and the link between information content and letter flows are of a different nature within versus between towns. Hence, in our main analysis, we focus on access to long-distance communication and exclude communication within towns from LMA .

Taking logs, we obtain the following equation

$$\ln L_{ni} = \ln A_i + \ln L_n - \gamma \ln d_{ni} - \eta \ln c_{ni} - \ln \sum_{i' \neq n} A_{i'} d_{ni'}^{-\gamma} c_{ni'}^{-\eta} \quad (3)$$

In standard gravity regressions, the terms $\ln A_i$ and $\ln L_n - \ln \sum_{i' \neq n} A_{i'} d_{ni'}^{-\gamma} c_{ni'}^{-\eta}$ would be absorbed by origin and destination fixed effects. Unfortunately, bilateral letter flows were never collected in Great Britain around the time of the reform. However, we have discovered a set of data on letter flows into London from 568 origin locations for one week in January 1838 (the pre-reform period).²⁹ To use this information, we have to fix $i = London$ and the letter-destination fixed effect will enter the regression as a constant. In addition, we cannot use letter-origin fixed effects, as we would have as many fixed effects as observations. On the other hand, we have measures of the travel costs d_{ni} and the cost of exchanging letters c_{ni} between location n and London.

To convert eq. 3 into an estimable equation, we need to posit a relation between letters, population, and A_i , and a way to control for the unobserved $\ln LMA$. We assume that the propensity of a place to

²⁹We focus specifically on regular letters, omitting from our analysis “privileged” letters (e.g., those sent for free by those with franking privileges) as well as newspaper flows, which were governed by a separate set of policies, though we do use those as controls in some of our analysis. Summary statistics for our letter flow data, and other variables used in our analysis of letter flows, are available in the Appendix, Table B1.

receive or send letters is a power function of local population, that is, $L_n = \beta_0 P_n^\beta$ and $A_i = \beta_1 L_i = \beta_1 \beta_0 P_i^\beta$. In the empirical specifications below, we explore alternative estimation approaches, we use an iterative procedure to recover the LMA term, and always include a set of ten regions fixed effects and other controls.

We adopt two alternative approaches to estimating our coefficients of interest: a simple cross-sectional regression, and a two-steps procedure that exploits the sharp increases in prices around the distance cutoffs.

In the first approach, we estimate the coefficients on population, distance and cost jointly (the “*joint*” approach). In particular, we estimate

$$\ln L_{ni} = \alpha_0 - \gamma \ln d_{ni} - \eta \ln c_{ni} + \beta \ln P_n - \ln \sum_{i' \neq n} P_{i'}^\beta d_{ni'}^{-\gamma} c_{ni'}^{-\eta} + \alpha' X_n + \varepsilon_n \quad (4)$$

In this expression, d_{ni} is the travel cost between post towns n and i computed over the combined waterways, rail, and turnpike networks in 1838, c_{ni} is the cost of exchanging letters pre-reform, and P_n is the 1838 population of the registration district in which the post town is located.³⁰ The term ε_n captures the sum of classical measurement error in the regressors. The X_n term includes a set of region fixed effects. Equation 4 contains the coefficients β , γ and η in the unobserved letter market access. To estimate it, we adopt an iterative procedure. Given any set of estimates $\hat{\beta}$, $\hat{\gamma}$ and $\hat{\eta}$, we can construct a proxy for LMA_n , denote it $\widehat{LMA}_{joint,po}$, as

$$\ln \widehat{LMA}_{joint,po}(\hat{\beta}, \hat{\gamma}, \hat{\eta}) = \ln \sum_{i' \neq n} P_{i'}^{\hat{\beta}} d_{ni'}^{-\hat{\gamma}} c_{ni'}^{-\hat{\eta}} \quad (5)$$

This proxy is the direct empirical counterpart to equation 2. The “*po*” superscript indicates that we are accounting for the fact that not all registration districts have post towns, which likely limited mail communications with those places. The summation is then taken only over districts where there is at least one post office. To estimate eq. 4, we start with an initial proxy for LMA which sets $\hat{\beta} = 1$ and $\hat{\gamma} = \hat{\eta} = -1$. We obtain a first set of elasticities, $\hat{\beta}$, $\hat{\gamma}$ and $\hat{\eta}$, which we use in 5 to obtain an updated estimate of $\widehat{LMA}_{joint,po}$. We can then re-estimate eq. 4, and obtain a new set of elasticities to insert in 5. We iterate over this procedure until the elasticities estimated in 4 are the same as those used to construct $\widehat{LMA}_{joint,po}$.³¹

In the Appendix, we also reproduce our results with an alternative proxy for LMA constructed as

$$\ln \widehat{LMA}_{joint,all}(\hat{\beta}, \hat{\gamma}) = \ln \sum_{i' \neq n} P_{i'}^{\hat{\beta}} d_{ni'}^{-\hat{\gamma}} \quad (6)$$

³⁰In a few cases, one registration district has more than one post town. In those cases, we assume that each post town serves an equal fraction of the population of the district.

³¹Our convergence criterion stops when all coefficients differ from the previous estimates by at most 0.1%.

where we use the entire set of registration districts in Great Britain, not only those where a post office is present, without discounting by communication costs. This formulation departs more from equation 2, but has the potential to better capture features of the local economy that would be absorbed by an origin fixed effect, because it also includes the population of (and distance to) locations where we do not observe a post office.

Our estimates of equation 4 are presented in Table 2. Column 1 looks at the relationship between distance and letter flows controlling only for region fixed effects, postage costs and travel costs. In Column 2 we add in controls for a location's population and then the proxy for access in Column 3. As each additional control is added, the impact of communication costs on letter volumes becomes larger and stronger. As expected, locations with a larger population send more letters to London. Locations with greater letter market access, indicating that they have more nearby population centers to communicate with, other than London, send fewer letters to London (controlling for their own size and travel costs to London). In our preferred specification, Column 3, we estimate that a doubling of the costs is associated with a 97% reduction of the volume of letters. Perhaps not surprisingly, distance and cost have a substantial and distinct impact on letter flows. Table B2 in the Appendix reproduces the most stringent specification of Column 4 using the alternative proxy $\widehat{LMA}^{joint,all}$.

Table 2: Impact of cost, distance, and population on letter flows

	DV: Log Letter Flows to London		
	1	2	3
\ln Postage Cost	-1.770** (0.745)	-2.573*** (0.639)	-3.452*** (0.704)
\ln Travel Costs, 1838	0.037 (0.174)	0.109 (0.151)	-0.143 (0.165)
\ln Population		1.084*** (0.092)	1.144*** (0.096)
$\ln \widehat{LMA}^{joint,po}$			-0.874*** (0.269)
Regions FE	Y	Y	Y
N	574	574	574
R^2	0.13	0.34	0.35

Robust standard errors in parentheses. * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

This joint estimation approach imposes a constant elasticity of distance and cost across all the range

of distances in our sample, and it mostly exploits variation of distance within cost bands to separately identify γ and η . On the other hand, it does not fully leverage the sharp discontinuity implied by the step-wise nature of the cost of sending letters pre-reform. In a second exercise, we adopt an iterative two-steps procedure (which we label “*ts*” approach). In the first step, we identify the effect of distance and population while flexibly controlling for costs; in the second step, we recover the effect of costs exploiting their discontinuous jump around distance thresholds. At each iteration, we recover estimates of β and γ in the first step, and η in the second step, and we use those estimates to form a new approximation for $\widehat{LMA}^{ts,all}$ as described above.

In particular, the first step estimates

$$\ln L_{ni} = \alpha_0 - \gamma \ln d_{ni} + \beta \ln P_n - \ln \sum_{i' \neq n} P_{i'}^\beta d_{ni'}^{-\gamma} c_{ni'}^{-\eta} + \alpha' X_n + \varepsilon_n \quad (7)$$

where X_n include a set of region fixed effects and cost brackets fixed effects. Since the cost for sending letters is constant within brackets, any remaining relationship between travel costs and letter flows is independent of the cost of sending letters. Table 3 reports the results. The effect of travel costs on letters to London becomes clear after we control for alternative destination options as captured by the proxy for *LMA*. Using cost bracket fixed effects rather than the log cost in this first step leads to a larger (and significant) travel costs elasticity of -0.65, and a slightly larger role for population. In Table B3 in the Appendix, we reproduce the last Column of this table using $\widehat{LMA}^{ts,all}$.

In the second step, we directly exploit the fact that postage costs are a step-function of distance. We focus on locations which are within 2.5 kilometers on one or the other side of a distance threshold where the postage cost changed.³² It is worth noting that our data include towns in every direction from London, so two locations at a similar distance are not necessarily near each other. Denoting the group of towns around a threshold B as G_B , we estimate:

$$\ln L_{ni} = \beta_0 - \mathbf{1}[n \in G_B] + \eta \ln c_{ni} + \ln \sum_{i' \neq n} P_{i'}^\beta d_{ni'}^{-\gamma} c_{ni'}^{-\eta} + \beta' X_n + \varepsilon_n \quad (8)$$

where $\mathbf{1}[n \in G_B]$ is a set of group dummies, and X_n include n -specific controls. The most important control is population, but we also explore the impact of other controls. The group bins flexibly control for different distances to London across sets of towns. Within each group, locations are at a similar distance to London, but because they fall on different sides of a cost step, post towns that are slightly further away experience a discrete jump in their postage costs. This second set of results offers a less parametric approach to controlling for distance. However, it also relies on a substantially smaller set of observations. The results of this second step are reported in Table 4.

³²This distance is the largest for which no post town is simultaneously to the right of one threshold and to the left of the next.

Table 3: Impact of distance and population on letter flows, controlling for cost

	DV: Log Letter Flows to London		
	1	2	3
\ln Travel Costs, 1838	0.040 (0.185)	0.113 (0.159)	-0.653** (0.304)
\ln Population		1.134*** (0.093)	1.194*** (0.096)
$\ln \widehat{LMA}^{ts,po}$			-1.375*** (0.474)
Letter cost FE	Y	Y	Y
Region FE	Y	Y	Y
N	574	574	574
R^2	0.14	0.36	0.37

Robust standard errors in parentheses. * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

We estimate cost elasticities ranging between -1.2 and -1.8; these estimates become more precise as controls are added. Column 1 only includes group threshold and region fixed effects. Column 2 controls for local population. In Columns 3 we include two controls that were not included in the previous Table 3. The first of these is the number of “privileged” letters sent from a location to London, i.e., letters that could be posted without charge (e.g., because a sender had franking privileges). This flow will reflect in part the impact of travel costs, but it will also capture other local features such as the presence of more MPs or government officials, that may have affected letter flows. Since this variable will reflect in part the role of travel, we do not want to include it in the previous table, where it is likely to be a bad control, but here it can help us control for additional factors other than cost that impact letter flows. The second new variable, newspaper flows, is included for a similar reason. Like privileged letter flows, newspaper flows were not subject to the same postage scheme as regular letters, so including this control helps us deal with unobserved local factors other than cost that may influenced letter flows. Columns 4 controls for our proxy for LMA . In our preferred estimation, the elasticity of letter cost to volume of letters is estimated at about -1.5. Table B4 in the Appendix reproduces the most stringent specification of Column 4 using the alternative proxies $\widehat{LMA}^{ts,all}$. ³³

³³It is worth noting that the estimates in tables 2 and 3 find a coefficient statistically indistinguishable from -1 on $\ln LMA$, as our model of letter flows in eq. 3 would predict. Note that our iterative procedure does not impose it, and in fact, when we use the $\widehat{LMA}^{::all}$ proxy – which does not include letter costs – rather than $\widehat{LMA}^{ts,all}$, the point estimate of the coefficient

Table 4: Impact of cost on letter flows

	DV: Log Letter Flows to London			
	1	2	3	4
\ln Postage Cost	-1.230 (1.719)	-1.789 (1.537)	-1.390 (0.868)	-1.534* (0.916)
\ln Population		Y	Y	Y
\ln Privileged Letters			Y	Y
\ln Newspaper Flows			Y	Y
$\ln \widehat{LMA}_1(TS)$				Y
Group threshold FE	Y	Y	Y	Y
Region FE	Y	Y	Y	Y
N	98	98	98	98
R^2	0.29	0.42	0.81	0.82

Robust standard errors in parentheses. * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

In summary, this analysis yields two main findings. First, it is clear (though not surprising) that postage costs reduce letter flows, and that this effect operates independently of travel costs, which also somewhat reduce letter flows. Second, this analysis provides specific estimates of the elasticity of letter flows with respect to postage costs, travel costs, and population. In our patents analysis, these elasticities are inputs in the construction of the size of the treatment that each location receives from the reform.

5 Main analysis

5.1 Citation data analysis

In this section, we analyze the impact of the reduction in communication costs generated by the postal reform on the exchange of scientific knowledge, as reflected in citations in scientific articles. Since these data provide a bilateral measure of knowledge flows between pairs of locations, we take advantage of standard approaches developed by trade economists for the study of how transport costs affect trade flows, an analog to our interest in how communication costs affect knowledge flows.

Using n subscripts to denote origin locations and i subscripts to denote destinations, our primary

on $\ln LMA$ becomes systematically more negative. We see this as an indirect test of the appropriateness of our letter flows model in eq. 1.

regression specification is,

$$CITE_{nit} = \beta COST_{ni} * POST_t + \xi_{nt} + \gamma_{it} + \psi_{ni} + \epsilon_{nit} \quad (9)$$

where $CITE_{nit}$ is the sum of citations in period t that originate from authors in post town n and are directed towards scientists in post town i . $COST_{ni}$ is the cost of sending a letter from location n to i in the pre-reform period, $POST_t$ is an indicator for the post-reform period, and ξ_{nt} , γ_{it} , and ψ_{ni} are, respectively, origin-period, destination-period, and dyad fixed effects. The inclusion of origin-time and destination-time fixed effects is natural given our data generating process, in which the publication of a single article by an author in an origin location can potentially include citations to a number of destination locations (and similarly, the publication of an article in a destination may lead to citations by subsequent articles in a number of origin locations). The inclusion of origin-time and destination-time fixed effects soaks up the impact of simply having an article appear, focusing attention instead on whether there are changes in the extent to which articles cite scientists in locations that were, in terms of postal cost, more distant.

The origin-time and destination-time fixed effects also absorb variation induced by three other factors. The first of these is the service provision of local penny posts, which served local areas around some post towns. The second is the presence of individuals with franking privileges, who were not treated by the reform because they could send letters at zero cost in the pre-reform period, at an origin or destination location. The third factor is the local impact of any changes in international postage rates. More generally, these fixed effects capture any origin trends and destination trends in unobserved factors that might have affected the number of articles or citations produced. The inclusion of dyad fixed effects is also important, since it will absorb fixed pair features including, most importantly, the distance between any two locations.

Recall from the data section that the unit of analysis in our citation data analysis is the post town. With over 600 post towns, our data set includes a large number of potential origin-destination pairs. Compared to this large matrix, the actual number of citations is relatively small, and the majority of connected pairs are connected by only one citation. Summary statistics are available in Appendix B.3. Given the sparsity of the citations data at the annual level, we collapse the data into one pre-reform period spanning 1830-39 and one post-reform period covering 1840-49.³⁴ We then estimate our specification using PPML. Note that the dyad fixed effects in Eq. 9 will cause origin-destination pairs with equal citation counts in both the pre- and the post-reform periods to drop out of the analysis.³⁵

Results of our analysis of the citation data are presented in Table 5. In Column 1, we present results with origin-time and destination-time fixed effects, but omitting dyad fixed effects. This allows us to separately estimate the impact of the distance-based postage cost on citations in the pre-reform period. The coefficient on the “Log Cost” variable tells us that citations are substantially lower between

³⁴Bertrand *et al.* (2004) also show that collapsing the data into two periods provides an effective way of addressing potential serial correlation concerns.

³⁵All regressions in this section report the number of observations effectively used in the estimation.

locations with higher bilateral postage costs in the pre-reform period. The coefficient on the “Log Cost x Post-reform” period indicates that locations with higher bilateral postage costs experienced a substantial relative increase in citations in the post-reform period. In terms of magnitude, the estimated increase in citations in the pre-reform period is large enough to offset roughly two-thirds to three-quarters of the penalty imposed by higher costs in the pre-reform period (with the difference likely due to other impacts of distance on citations that were independent of cost). Put another way, our results indicate that roughly two-thirds to three-quarters of the decay of knowledge exchange with distance, as reflected in citations, disappears as a result of the reform.

In Column 2, we include dyad fixed effects. These absorb the impact of pre-reform costs as well as any other time-invariant factor related to bilateral distance. However, the inclusion of this large set of additional fixed effects has very little impact on the estimated effect of the postal reform. Note that the sample size falls in this regression because any dyad without any citations will drop out. In Column 3, we go even further, by including directed dyad fixed effects. Even this very stringent specification results in very little change in the estimated effect of the reform on bilateral citations.

In Columns 4-6 we estimate similar results but using an alternative approach to calculating standard errors. Specifically, in place of the robust standard errors used in Columns 1-3, we cluster standard errors at the origin-period level.³⁶ This allows for the possibility that standard errors may be correlated across dyads within a period because the citations originated from the same article. Allowing for this type of correlation has very little impact on the statistical significance of our results.

The estimated coefficients in Table 5 suggest that the elasticity of citations with respect to a reduction in postage cost is between 0.62 and 0.73. One way to interpret this is relative to a one standard deviation reduction in the log cost, 0.36, which would imply an additional 0.22 to 0.26 citations between a dyad, relative to a sample mean of 0.18 citations in the pre-period estimation sample. Or put another way, the change in log cost between our average-cost and lowest-cost dyads in the sample was about 1.5 log points, so lowering the postage cost for the average cost dyad to that of the lowest would lead us to expect around one additional citation over the ten-year post-reform period. Of course, these figures only apply to locations where a cited scientist was present sometime during our sample period.

To summarize, our citation results show clear evidence that scientific citations increased between location pairs that experienced a greater reduction in bilateral postage costs as a result of the introduction of the uniform penny post. These results are found using a fairly strong analysis strategy that accounts for location-time and location-pair fixed effects. While the economic importance of the additional citations is difficult to assess, the fact that citations respond strongly to reduced communication costs indicates that reducing the cost of long-distance communication played a meaningful role in facilitating knowledge

³⁶We have fewer origin locations than destinations, so this is more stringent than clustering by destination-time. It is also more sensible, since the most likely source of correlated standard errors across citations is that they originate from the same article. We have also experimented with multidimensional clustering at the dyad, origin and destination level, finding the same levels of significance.

Table 5: Citations analysis results

DV: Number of citations between an origin-destination pair in a period						
	Robust Standard Errors			SEs clustered by origin-period		
	1	2	3	4	5	6
Log cost	-0.928*** (0.188)			-0.928*** (0.172)		
Log cost x post-reform	0.621** (0.269)	0.718*** (0.253)	0.731*** (0.242)	0.621** (0.296)	0.718*** (0.246)	0.731*** (0.226)
Citing Loc. x Period FE	Y	Y	Y	Y	Y	Y
Cited Loc. x Period FE	Y	Y	Y	Y	Y	Y
Dyad FE	N	Y	N	N	Y	N
Directed Dyad FE	N	N	Y	N	N	Y
<i>N</i>	4,524	364	220	4,524	364	220

In Columns 1-3, robust standard errors are presented in parenthesis. In Columns 4-6, standard errors are clustered by origin-period. * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

exchange between scientists. Next, we consider whether lower communication costs also facilitated the development of new technologies.

5.2 Patent data analysis

Analyzing patent data provides a useful complement to our analysis of scientific citations. The new technologies represented by new patent files provide a second margin along which we can assess the impact of lower communication costs, and one that is particularly important for productivity and economic growth.

The nature of the patent data implies that this analysis will differ in important ways from our analysis of citation data. Most importantly, the patent data represent a location-level rather than a bilateral pair-level outcome. This feature has two consequences. First, it means that we need to construct a location-level measure of treatment. Second, it means that we will have to control for factors such as the remoteness of a location, its market access, or the presence of a railroad connection, instead of being able to include fixed effects that absorb these concerns.

To construct a location-level measure of the impact of the postal reform, we use an approach similar to the market access measure of ([Donaldson & Hornbeck, 2016](#)). As we have argued in Section 4, one can

think of the letter market access as a measure that captures the availability of communication opportunities for residents of a particular place. This measure is a function of letter costs, but also of distance and population. The postal reform only changes the cost. Consequently, the change in letter market access for location n implied by the reform – a measure of the treatment received by location n – can be defined as

$$\Delta LMA_n = \underbrace{\ln \left(\sum_{i' \neq n} P_i^\beta d_{ni'}^{-\gamma} 1^{-\eta} \right)}_{LMA_{n,after}} - \underbrace{\ln \left(\sum_{i' \neq n} P_i^\beta d_{ni'}^{-\gamma} c_{ni'}^{-\eta} \right)}_{LMA_{n,before}} \quad (10)$$

This value can now be computed, since P_n is the local population in n , d_{ni} is the bilateral travel cost over the waterways, rail and turnpike networks, and c_{ni} the postage cost between locations n and i in the pre-reform period, all observed; furthermore, the elasticities β , γ and η have been estimated in Section 4. Our preferred specification uses estimates of the elasticities from tables 3 and 4, which are based on a less parametric approach. However, we also present results based on the joint estimation approach, from Table 2. We explore the robustness of our results to alternative methods of calculating treatment in Appendix B.5.

Equipped with a measure of the treatment size for a location, ΔLMA_n , we can now analyze the impact of the reform on new patents using standard panel data methods. The unit of observation in our patent data is the post town and, as in the citation analysis, we collapse the data into one pre-reform period (1830-39) and one post-reform period (1840-49). Since, even in the collapsed data, patents are sparse at the location-by-period level for many smaller locations, we estimate results using PPML. London is excluded entirely from our patent analysis because it produced far more patents than any other location and likely had a much different innovation environment (and one that was likely to be much less affected by the fall in postage costs). Our patent analysis regression specification is,

$$PAT_{nt} = \beta_0 POST_t + \beta_1 (\Delta LMA_n \times POST_t) + X_{nt}\Gamma + \eta_n + \epsilon_{nt} \quad (11)$$

where PAT_{nt} is the number of patents associated with post town n in period t , ΔLMA_n is defined above, $POST_t$ is an indicator for the post-reform period, X_{nt} is a set of control variables, and η_n is a set of post town fixed effects. In our preferred specification, we include controls for local population, market access, and county-by-decade fixed effects. Market access is defined as

$$MA_n = \left(\sum_{i' \neq n} P_i d_{ni'}^{-\theta} \right) \quad (12)$$

and it captures a measure of economic opportunity of location n , as proxied by its travel costs-weighted

proximity to all population centers in Great Britain. Note that we exclude the own population of location n since such population will always be present as a separate regressor in our analysis. The elasticity θ , the “trade elasticity” in the trade literature, captures the effect of space-related frictions on economic activity. We will use $\theta = 4$, close to [Simonovska & Waugh \(2014\)](#), but we experiment with a grid encompassing most other estimates found in the literature in Appendix [B.5](#).

Regression results for our patent data analysis are presented in Table [6](#). In all regressions, we cluster the standard errors at the Registration District \times period because population information only comes at this broader level of aggregation, and some post towns are located in the same District. Column 1 presents the most parsimonious specification, without controls for population, market access, or other time-varying factors, using LMA parameters obtained from the two-step estimation approach shown in tables [3](#) and [4](#). We estimate a positive association between the change in letter market access induced by the treatment and the number of patents, but this relationship is not statistically significant. In Column 2, we add in controls for population and market access. With these controls included, we begin to observe a stronger and statistically significant relationship between the change in letter market access and patents.

In Column 3, we include county-by-decade fixed effects. These fixed effects help us deal with the fact that the Industrial Revolution was heavily concentrated in certain regions of the country, such as Lancashire, the West Riding, and the Midlands, while other areas were left behind. The inclusion of county-by-decade controls can help account for these substantial regional differences. This within-county comparison means we are identifying our estimates off of less variation, in terms of the change in letter market access, but it also means we are comparing locations exposed to more similar economic conditions. With these controls included, we find an even clearer relationship between the change in letter market access and the number of patents in a location. However, we can also see, from the results in Column 2, that the inclusion of these fixed effects is not vital for generating significant results.

In Columns 4–6, we replicate the same exercise, but using the letter market access measures based on the parameters obtained from the joint estimation approach (i.e., Table [2](#)). This gives very similar results, which indicates that our findings are not sensitive to which of these approaches we use.^{[37](#)}

In terms of magnitude, our preferred estimates in Columns 2–3, suggests that location that experienced a one standard deviation greater improvement in letter market access as a result of the reform would have produced, on average, an additional 0.98 to 0.22 patents during the post reform period. This is equivalent to a 2.6% to 5.9% increase in the average number of patents produced by locations in the pre-reform period.

In Appendix [B.5](#), we report results where we vary the trade elasticity used in market access, we consider elasticities estimated from both the two-step and the joint estimation approaches described in Section [4](#), and also use treatments computed not allowing (“*po*”) or allowing (“*all*”) communications with

³⁷The increase in the coefficients between columns 2 and 3, or 5 and 6, is not a consequence of the slightly different estimation sample that results after introducing the fixed effects; re-estimating columns 2 and 4 on the estimation samples in columns 3 and 6 yields essentially unchanged estimates.

Table 6: Patent data analysis results

Treatment:	DV: Number of patents					
	Two-steps estimation			Joint estimation		
	1	2	3	4	5	6
Post	0.596*** (0.044)	0.444*** (0.127)		0.598*** (0.045)	0.440*** (0.128)	
$\Delta LMA_n \times \text{Post}$	0.066 (0.042)	0.096** (0.046)	0.219** (0.087)	0.057 (0.039)	0.092** (0.044)	0.302*** (0.115)
$\ln \text{Population}$		0.903* (0.509)	0.271 (0.744)		0.928* (0.507)	0.308 (0.769)
$\ln MA$		0.033 (0.133)	0.107 (0.139)		0.047 (0.136)	0.127 (0.139)
Post Town FE	Y	Y	Y	Y	Y	Y
County \times Decade FE	N	N	Y	N	N	Y
N	678	678	658	678	678	658

$\Delta LMA^{\cdot po}$ and $\ln MA$ have been standardized. Standard errors clustered by registration district \times period in parentheses. * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

districts without post offices.

Table B7 in the Appendix reproduces columns 2-3 and 5-6 of Table 6 when the trade elasticity θ varies over a grid of integers between 1 and 13. These values encompass most of the estimates found or used in the literature, like [Harris \(1954\)](#) ($\theta = 1$), [Bernard et al. \(2003\)](#) ($\theta = 3.6$), [Simonovska & Waugh \(2014\)](#) ($\theta = 4.14$), [Eaton et al. \(2011\)](#) ($\theta = 4.87$), [Costinot et al. \(2011\)](#) (θ between 2.7 and 6.7), [Eaton & Kortum \(2002\)](#) ($\theta=8.28$, with upper range extending to $\theta = 12.86$).

Table B8 reproduces our main Table 6 using the alternative approach to constructing the treatment, $\Delta LMA^{\cdot all}$, which uses all districts rather than focusing on those with a post office. The estimated effect of the reform is very similar when this alternative approach is used.

The key message from these robustness exercises is that our results are extremely stable across all the alternative approaches.

The evidence in this subsection indicates that the reduction in communication costs induced significant increases in patenting activity in more exposed relative to less exposed post towns. Taken together, the findings in this section are consistent with a central role of reduction in communication costs in enhancing the circulation of scientific knowledge and the creation of new ideas.

One lingering question to emerge from the preceding analysis has to do with the extent to which the technological developments reflected in the patent data may have been linked to the basic science reflected in the citation data. This issue – the link between basic science and technological development during the Industrial Revolution – is the subject of a long and ongoing debate among economic historians (see, e.g., [Landes \(1969\)](#), [Rosenberg \(1974\)](#), [Mokyr \(2002\)](#), [Khan \(2018\)](#), [Jacob \(2014\)](#), and [Kelly & Ó Gráda \(2020\)](#)). Establishing the direct link between scientific knowledge and technological development has often proven elusive, mainly because it is often difficult to establish links between basic science and new technologies. However, there seems little doubt that over a sufficiently long time horizon, technological development depends crucially on the development of basic scientific knowledge.

6 Conclusions

Economists have long suspected that the changes in the cost of exchanging knowledge are likely to influence the rate at which useful new ideas are developed. [Mokyr \(2005b\)](#), for example, writes that, “access to useful knowledge created the opportunities to recombine its components to create new forms that would expand the volume of knowledge at an even faster rate.” By taking advantage of the large and spatially varied reduction in communication costs resulting from the introduction of the Uniform Penny Post, our study provides more direct evidence on the impact of communication costs on innovation rates and the exchange of scientific knowledge than has heretofore been available. Our findings confirm the long-held belief that knowledge flows matter for science and innovation, and help place the extensive theoretical literature embodying these ideas on a more solid empirical foundation.

Establishing a link between communication costs and innovation has particular significance for some theories of endogenous growth. For example, in discussing the sources of sustained increase in the standards of living in modern capitalist economies, [Lucas \(2009\)](#) argues, “What is central, I believe, is the fact that the industrial revolution involved the emergence (or rapid expansion) of a class of educated people, thousands—now many millions—of people who spend entire careers exchanging ideas, solving work-related problems, generating new knowledge.” Our results suggest that the “generation” of ideas is intimately linked to the “exchange” of ideas, and they speak to a large growth literature which assumes ideas diffusion as an engine of economic growth. Our findings are also significant for our understanding of cities. As [Davis & Dingel \(2019\)](#) write, “Leading empiricists and theorists of cities have recently argued that the generation and exchange of ideas must play a more central role in the analysis of cities.” A natural implication of our results is that proximity, one way of reducing communication costs, facilitates the exchange of ideas, so that cities are also accelerating the generation of new knowledge. This may help explain why so much innovation takes place in cities.

Our results also contribute to our understanding of innovation in Britain during the Industrial Revolution. Joel Mokyr has argued that “The true miracle is not that the Industrial Revolution happened, but that it did not peter out like so many earlier waves of innovation” ([Mokyr, 2004](#)). Our findings suggest

that institutional reforms may have played an important role in sustaining technological progress during this crucial period of economic history.

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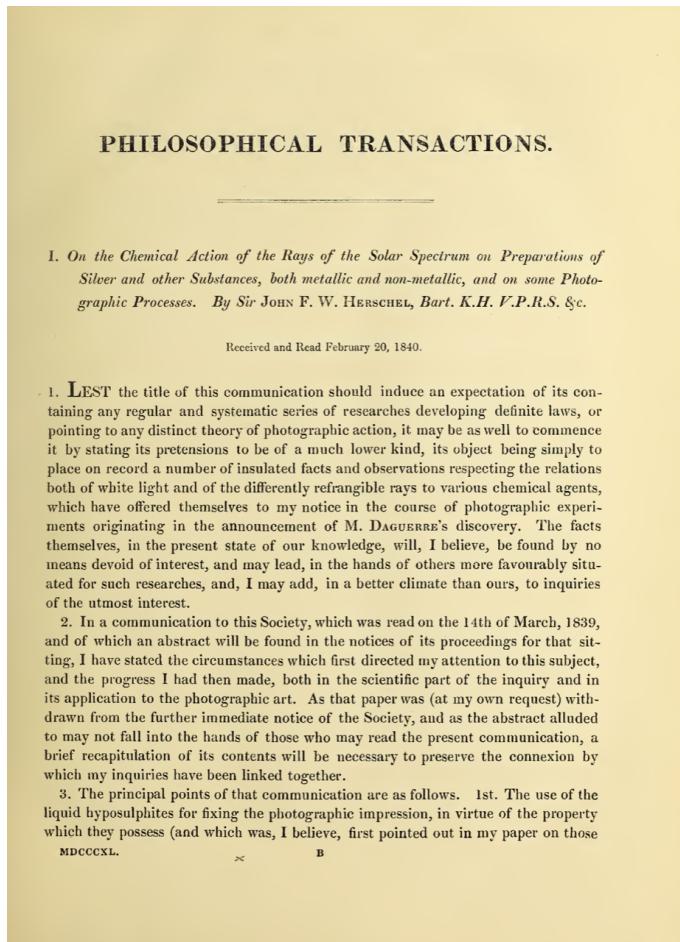
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A Additional Figures

Figure A1: An example of citations in the *Philosophical Transactions*



Note: This figure reproduces the first page of the first article that appeared in the 1840 issue of the *Philosophical Transactions*. "M. DAGUERRE" in the middle of the first paragraph is the first citation in this article. The cited inventor is Monsieur Louis-Jacques-Mandé Daguerre, who invented the first photographic process.

Figure A2: Patents filed during the study period



B Additional Tables

B.1 Summary statistics for letter flow analysis

Table B1 presents summary statistics for the variables used in the main letter flows analysis of Section 4. “Letters” is the number of letters sent to London from other post towns around Great Britain in the week starting January 15, 1838. This flow is calculating by subtracting the number of privileged letters from the total number of letters sent as reported in the original source table. “Travel Costs, 1838” is the travel cost between the centroid of the post town and London, computed over waterways, turnpike road, and rail network in 1838, as described in Section 3.4. “Population” is the population of the Registration District where the post town belongs in 1838. The variables $\widehat{LMA}_{joint,po}$ and $\widehat{LMA}_{ts,po}$ are the two alternative approximation to the letter market access of a post town, recovered as described in Section 4 in the main text.

Table B1: Summary statistics for data used in the analysis of letter flows

Variable	Obs	Mean	Std. Dev.	Min	Max
In Levels					
Letters	574	263.667	473.658	1	5660
Travel Costs, 1838	574	187.215	111.555	17.908	509.623
Population	574	.024	.018	.002	.211
$\widehat{LMA}_{joint,po}$	574	.001	.001	0	.012
$\widehat{LMA}_{ts,po}$	574	.006	.003	.003	.032
In Logs					
\ln Letters	574	4.867	1.159	0	8.641
\ln Travel Costs, 1838	574	5.028	.685	2.885	6.234
\ln Population	574	-3.872	.545	-6.082	-1.558
$\widehat{LMA}_{joint,po}$	574	-7.094	.366	-7.794	-4.452
$\widehat{LMA}_{ts,po}$	574	-5.176	.377	-5.979	-3.446

B.2 Robustness of letter flows regressions

Table B2 presents a robustness exercises for Table 2 in the paper, where we estimated jointly the elasticity of letter flows to population, distance and postage cost. In this table, column 1 replicates the last column of Table 2; column 2 repeats those estimates using $\widehat{LMA}^{joint,all}$ as a control for letter market access.

Table B2: Impact of distance on letter flows (robustness)

	DV: Log Letter Flows to London	
	1	2
Ln Postage Cost	-3.452*** (0.704)	-2.297*** (0.653)
Ln Travel Costs, 1838	-0.143 (0.165)	-0.355 (0.287)
Ln Population	1.144*** (0.096)	1.117*** (0.095)
Ln $LMA^{joint,po}$	-0.874*** (0.269)	
Ln $LMA^{joint,all}$		-2.268* (1.233)
Region FE	Y	Y
N	574	574
R ²	0.35	0.35

Robust standard errors in parentheses. * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Table B3 presents robustness exercises for Table 3 in the paper, where we estimated the elasticity of letter flows to population and distance controlling for costs, in the first step of our two-steps procedure. In this table, column 1 replicates the last column of Table 3; column 2 repeats the estimate using $\widehat{LMA}^{ts,all}$ as the approximation for the letter market access.

Table B4 presents robustness exercises for Table 4 in the paper, where we estimated the elasticity of letter flows to costs using a discontinuity design, the second step of our two-step procedure. In this table, Column 1 replicates the last column of Table 4; Column 2 repeats this estimate using $\widehat{LMA}^{ts,all}$ as an approximation for the letter market access.

Table B3: Impact of distance and population on letter flows, controlling for cost (robustness)

DV: Log Letter Flows to London		
	1	2
<i>Ln</i> Travel Costs, 1838	-0.653** (0.304)	-0.732* (0.380)
<i>Ln</i> Population	1.194*** (0.096)	1.184*** (0.095)
<i>Ln</i> $\widehat{LMA}^{ts,po}$	-1.375*** (0.474)	
<i>Ln</i> $\widehat{LMA}^{ts,all}$		-1.740** (0.738)
Letter cost FE	Y	Y
Region FE	Y	Y
<i>N</i>	574	574
<i>R</i> ²	0.37	0.37

Robust standard errors in parentheses. * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Table B4: Impact of cost on letter flows (robustness)

DV: Log Letter Flows to London		
	1	2
Ln Postage Cost	-1.534* (0.916)	-1.393 (0.862)
$Ln \widehat{LMA^{ts,po}}$	Y	
$Ln \widehat{LMA^{ts,all}}$		Y
Ln Population	Y	Y
Ln Privileged Letters	Y	Y
Ln Newspaper Flows	Y	Y
Group threshold FE	Y	Y
Region FE	Y	Y
N	98	98
R^2	0.82	0.81

Robust standard errors in parentheses. * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

B.3 Summary statistics for the citations analysis

Table B5 presents summary statistics for the estimation sample of citations across directed post town dyads in the citation data, by period. “Pre-reform” refers to the period 1830-1839, and “Post-reform” refers to the period 1840-1849. A directed dyad counts citations from location n towards scientists in location i separately from citations from location i towards scientists in location n . It also presents statistics on the log postage cost pre-reform.

Table B5: Summary statistics for the citations data

Variable	Obs	Mean	Std. Dev.	Min	Max
Citations pre-reform	2328	.18	1.212	0	30
Citations post-reform	2196	.177	1.244	0	38
Log pre-reform bilateral postage cost	2328	2.533	.36	1.099	3.114

B.4 Summary statistics for the patent analysis data

Table B6 presents summary statistics for the estimation sample in the patents analysis exercise. “Pre-reform” refers to the period 1830-1839, and “Post-reform” refers to the period 1840-1849. “Patents” is the count of patents filed in a location. $\Delta LMA^{m,v}$ is the exposure to the reform calculated using either the joint estimation or the two-steps method, $m \in \{joint, ts\}$ as described in Section 4, and either versions one or two of our proxy for the letter market access \widehat{LMA}_v , $v \in \{po, all\}$, as described in equations 5 and 6. “Population” is the population in the Registration District where the post town is located. “Market access” is the inverse of the travel costs-weighted sum of the population for all Registration Districts in Great Britain, as computed from the perspective of the registration district where the post town is located (eq. 12), using a trade elasticity $\theta = 4$. For the purposes of the patents-level analysis, the measures of exposure to the reform and the log market access have been standardized to provide comparability across specifications.

Table B6: Summary statistics for the patent analysis data

Variable	Obs	Mean	Std. Dev.	Min	Max
Patents, pre-reform	339	3.726	15.798	0	194
Patents, post-reform	339	6.578	27.006	0	340
$\Delta LMA^{ts,po}$	339	0	1	-4.008	2.561
$\Delta LMA^{ts,all}$	339	0	1	-3.897	2.655
$\Delta LMA^{joint,po}$	339	0	1	-3.736	2.176
$\Delta LMA^{joint,all}$	339	0	1	-3.685	2.31
Ln Population, pre-reform	339	-3.758	.541	-5.375	-1.663
Ln Population, post-reform	339	-3.657	.575	-5.325	-1.421
Ln Market access, pre-reform	339	-.265	.927	-2.396	3.391
Ln Market access, post-reform	339	.289	1.001	-2.212	3.463

B.5 Robustness of patent data analysis

Tables B7 and B8 present robustness exercises for the last column of the patent analysis in Table 6 in the paper.

Table B7 reports the effect of the reform (the coefficient on $\Delta LMA^{**} \times Post$) varying the trade elasticity θ used to compute market access between 1 and 13: this range covers most of the estimates in the literature. Columns 1 and 2 consider the two-step estimation approach (in parallel to column 2 and 3 of Table 6), while Column 3 and 4 consider the joint estimation approach (in parallel to column 5 and 6 of Table 6). Columns 2 and 4 include county-by-decade fixed effects, while columns 1 and 3 do not.

Table B7: Patent data analysis results: robustness for $\widehat{LMA}^{\cdot,po}$

Coefficient on:	DV: Number of patents			
	$\Delta LMA^{ts,po} \times \text{Post}$	$\Delta LMA^{joint,po} \times \text{Post}$	1	2
Trade Elasticity θ	1	2	3	4
$\theta = 1$	0.096** (0.047)	0.209** (0.087)	0.087** (0.044)	0.295*** (0.114)
$\theta = 2$	0.093** (0.046)	0.207** (0.089)	0.089** (0.043)	0.288** (0.116)
$\theta = 3$	0.095** (0.046)	0.215** (0.087)	0.092** (0.044)	0.297*** (0.115)
$\theta = 4$	0.096** (0.046)	0.219** (0.087)	0.092** (0.044)	0.302*** (0.115)
$\theta = 5$	0.095** (0.046)	0.220** (0.087)	0.091** (0.044)	0.302*** (0.116)
$\theta = 6$	0.095** (0.046)	0.220** (0.087)	0.091** (0.044)	0.302*** (0.116)
$\theta = 7$	0.096** (0.046)	0.219** (0.087)	0.091** (0.044)	0.301*** (0.116)
$\theta = 8$	0.096** (0.046)	0.219** (0.087)	0.091** (0.044)	0.301*** (0.116)
$\theta = 9$	0.096** (0.046)	0.219** (0.087)	0.092** (0.044)	0.300*** (0.116)
$\theta = 10$	0.097** (0.046)	0.219** (0.087)	0.092** (0.044)	0.300*** (0.116)
$\theta = 11$	0.097** (0.046)	0.219** (0.087)	0.093** (0.044)	0.300*** (0.116)
$\theta = 12$	0.097** (0.046)	0.219** (0.087)	0.093** (0.044)	0.300*** (0.116)
$\theta = 13$	0.097** (0.046)	0.219** (0.087)	0.093** (0.044)	0.299*** (0.116)
Post Town FE	Y	Y	Y	Y
County \times Decade FE	N	Y	N	Y
N	678	658	678	658

ΔLMA has been standardized. Standard errors clustered by registration district \times period in parentheses. * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Table B8 replicates the entire analysis of Table 6 where all the relevant elasticities have been estimated using $\widehat{LMA}^{m,all}$ rather than $\widehat{LMA}^{m,po}$, where $m \in \{ts, all\}$.

Table B8: Patent data analysis results: robustness for $\widehat{LMA}^{*,all}$

Treatment:	DV: Number of patents					
	Two-steps estimation			Joint estimation		
	1	2	3	4	5	6
Post	0.594*** (0.044)	0.447*** (0.126)		0.598*** (0.045)	0.440*** (0.128)	
$\Delta LMA_n \times Post$	0.068 (0.042)	0.095** (0.045)	0.184** (0.077)	0.060 (0.039)	0.094** (0.044)	0.301*** (0.112)
Ln Population		0.883* (0.506)	0.237 (0.726)		0.927* (0.507)	0.308 (0.766)
Ln MA		0.023 (0.132)	0.098 (0.140)		0.044 (0.135)	0.122 (0.139)
Post Town FE	Y	Y	Y	Y	Y	Y
County \times Decade FE	N	N	Y	N	N	Y
N	678	678	658	678	678	658

ΔLMA_n and Ln MA have been standardized. Standard errors clustered by registration district \times period in parentheses. * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

C Construction of the Post Town network

This section explains how we create the network of post roads and post towns from historical maps and records.

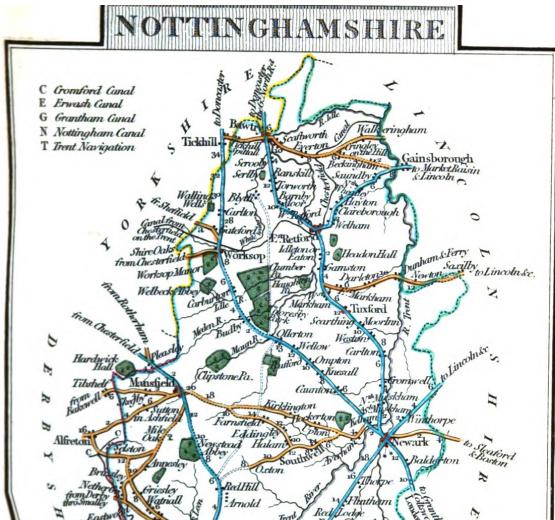
Post Towns Our list of post towns in 1838 is taken from a publication by the *Select Committee on Postage*. It lists 862 post towns and over 1,600 subpost towns in England, Scotland or Wales that are organized into eight regional post districts.

To geolocate the post and subpost towns, we first make use of the Google Geolocation API. Since some post town names are not unique (e.g. Bradford), this procedure comes with some imprecision. To overcome this and assess the validity of the geolocation exercise, we exploit the spatial clustering in the data that is implicitly provided by the assignment of post towns to postal districts. Specifically, we check if all coordinates from the same postal district are clustered and correct outliers manually using historical gazetteers and maps. This procedure leaves us with the centroids of all post towns and subpost towns that are shown in Figure 3 in the main text.

Post Roads To create the post road network, we start with Cary (1828) who provides detailed maps of the road network and supplement it with the more stylized postal road network published in Basire (1838). Figure A3 shows an excerpt from both publications. Specifically, we take the locations of post towns from the previous geolocation exercise as given and connect them with contemporary B-roads that approximate the historical location of the roads shown on the maps. While this procedure introduces some measurement error from potential changes in the exact route, it comes with the important benefit that road locations implicitly take terrain into consideration. We then use post town locations and post roads to create a road network in ArcGIS that allows us to route between locations. To connect post towns to the postal route network, we create straight line minimum-distance connections between the centroid and the postal road network and assign zero-distance to these connector bits. The rationale is that we do not consider costs of sending letters within post towns and therefore assume that every post town is located along the post road.

To test how well our postal network approximates historical travel distances, we make use of information on the road distance between London (Edinburgh) and all English or Welsh (Scottish) post towns published by the *Select Committee on Postage* and compare it to calculations based on our own road network. Figure A4 shows the results of this exercise. It is reassuring to see that all observations tightly fit the 45 degree line, suggesting that our network does a good job approximating historical travel distances. The fit is particularly tight in England and a bit more noisy in Scotland. Further inspection suggests that these differences result from locations in the highlands, suggesting that in this rugged terrain, modern roads do not approximate historical roads so well. These differences are of little concern to our analysis

Figure A3: Historical Maps



(a) Cary 1828



(b) Basire 1838

This figure shows excerpts from Cary (1828) and Basire (1838) maps which were digitized to compute postal network routes.

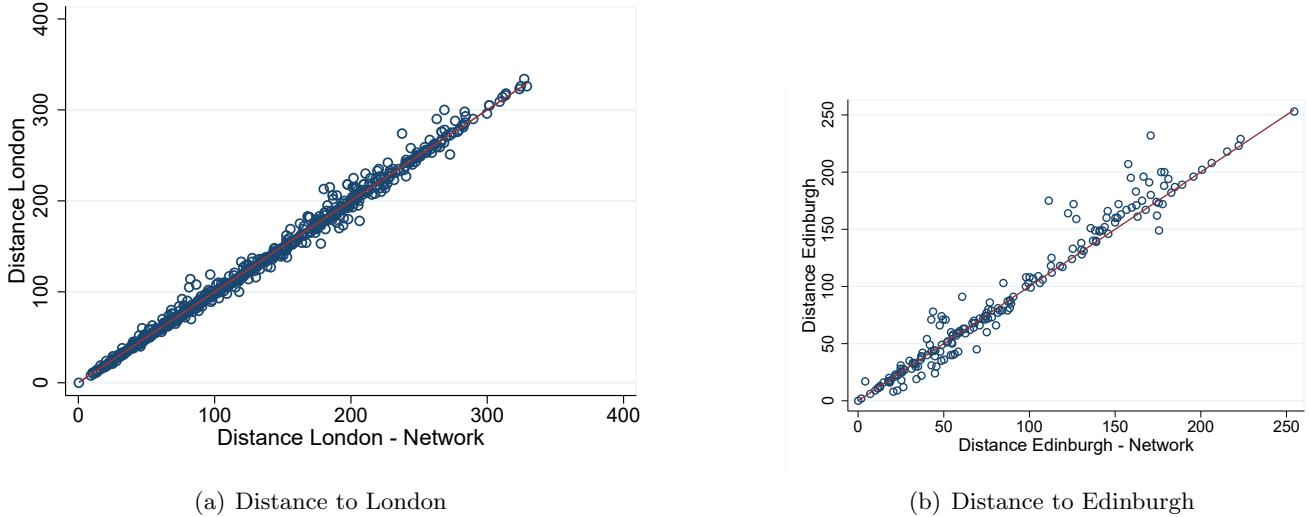
since we do not use Scotland in the analysis of patent data and we only observe very few authors located in the Highlands.

Connections We are ultimately interested in the costs of sending a letter between locations of scientists or inventors. To link scientists' locations to the postal network, we assign each author to the nearest subpost town or posttown and use a post office publication that links each subpost towns hierarchically to a post town to calculate the costs of sending a letter between post offices. We neglect the costs of sending a letter between subpost towns and post towns and post offices since they were typically a flat fee of a penny that would likely apply to all flows. In the worst case, this would imply that we are understating the change in communication costs. Since we do not have address-specific patent data but only observe the applicants home town, we geolocate all home town locations and then link each patentee location to the nearest subpost town or post town.

D Calculation of Postage rates

This section explains how we calculated the total cost of exchanging letters between the post towns. The total cost are determined by two components, a distance-dependent component that measures the costs

Figure A4: Comparison



Note: This figure shows historical distances reported in 1838 compared to the network calculations.

for exchanging a letter between a pair of post towns, and a local cost component which takes delivery at the origin and destination post town into account.³⁸

Distance-dependent Rates We use the distance-dependent postage rates for single-sheet letters that are provided in [Postage Act \(1812\)](#) and shown in figure 1.³⁹ Table B9 displays the pre-reform postage rate schedule, including the rates for multiple-sheet letters and an additional cost bin for local letters up to 8 miles that was introduced on 6 January 1838 ([Postage Act, 1837](#)). We decide in favor of a time-invariant pre-reform cost measure and prescind from incorporating this local rate change in our analysis.⁴⁰

We employ our network of post towns and post routes to calculate a distance matrix that contains the distance between each possible pair of post towns. We apply the above described rates to these distances to determine the distance-dependent cost component.

The Postage Act of 1812 introduced an additional half penny for every letter that travelled through Scotland. We take this into account by adding half a penny to all connections that involve at least one Scottish post town.

³⁸Not all inventors and scientists lived directly in one of the 618 post towns.

³⁹Single-sheet letters accounted for more than 90 percent of all letters in Great Britain in the pre-reform period ([Select Committee on Postage, 1838](#)).

⁴⁰From 18 September 1838 on, rates were determined by the distance along the shortest public road and not the route sent if different. Our measure of postage costs is based on the rates that were effective from 1830 to 1837. We expect that the changes in 1838 will result in a slight push of our estimated treatment effects toward zero.

Table B9: Costs of sending a letter in 1838

Mileage	Single	Double	Treble	Ounce	+ea. 1/4oz
Up to 8 miles	2d	4d	6d	8d	+ 2d
8-15 miles	4d	8d	1s	1s 4d	+ 4d
15-20 miles	5d	10d	1s 3d	1s 8d	+ 5d
20-30 miles	6d	1s	1s 6d	2s	+ 6d
30-50 miles	7d	1s 2d	1s 9d	2s 4d	+ 7d
50-80 miles	8d	1s 4d	2s	2s 8d	+ 8d
80-120 miles	9d	1s 6d	2s 3d	3s	+ 9d
120-170 miles	10d	1s 8d	2s 6d	3s 4d	+ 10d
170-230 miles	11d	1s 10d	2s 9d	3s 8d	+ 11d
230-300 miles	1s	2s	3s	4s	+ 1s
Each extra 100 miles	+1d	+2d	+3d	+4d	+ 1d

This figure shows how postage rates increase with distance. Single, double, treble refers to the number of sheets. d: penny; s: schilling; $12d = 1s$.

Local Rates Local penny post offices were in charge of delivering the mail within post towns and connecting the surrounding smaller villages to the post towns. We add a penny at both the origin and destination location for local delivery from the local penny post office closest to the author to the origin post town and for the local delivery from the destination post town to the penny post office closest to the cited scientist. Some authors and scientists lived directly in the origin or destination post town, so we are again overstating postage. As almost all local penny posts charged a penny for single-sheet letters, we are also assuming a rate of one penny if two scientists lived in the same post town.

There are two exceptions to the above description. The London Twopenny Post and the Edinburgh Penny Post both covered a sizeable area and had specific rates that exceeded those of the other local Penny Posts. We reconstructed the elliptic coverage area of the Edinburgh Penny Post based on the description in [Select Committee on Postage \(1838\)](#), Appendix p. 171. The rate for using the services of the Edinburgh Penny Post was either one penny or two pence depending on the distance between the respective local penny post office and the main post office at HM Register House. We apply a rate of 1.5 pence for local delivery in and around Edinburgh.

The London Twopenny Post consisted of two separate areas with different associated rates. The town area covered all parts of London that were within a three-mile radius around the General Post Office in St Martin's Le Grand. The country area covered the suburbs outside the three-mile but within a twelve-mile radius around the General Post Office. Letters that were posted and delivered within the town area cost 2 pence. Delivery from the General Post Office to the town area or vice versa was free. Delivery from

the General Post Office to the country area or vice versa was 2 pence and delivery from the town to the country area or vice versa was 3 pence as was within-country delivery (see [Hemmeon, 1912](#)).

E Construction of the Citation Dataset

E.1 Summary Statistics

Between 1830 and 1849, 443 articles appeared in the *Philosophical Transactions of the Royal Society of London*. Table [B10](#) displays basic descriptive statistics for this population at the year, period, and aggregate level.

About 57 percent of all articles and pages were published before the introduction of uniform penny postage. Articles continued to span about twenty pages on average but journal space became more evenly distributed among authors over time.

In the period that we study, it was not uncommon for an individual author to publish multiple articles in the same issue. This explains why the number of articles exceeds the number of authors in most years. Co-authorship was rare, but some articles still represent joint work. These articles typically state a single author but include notes by other scientists that often extend to several pages. Table [B10](#) only takes official co-authorship into account (only one article was coauthored, the first article published in 1844).

Three articles in the sample contain sizable parts that were written by scientists other than the stated authors. These three articles and the mentioned 1844 article were split up to attribute each forward citation to its origin. One of the three articles was published in the pre-reform period, the other two appeared in the post-reform period, leading to article counts of 252 in the pre- and 195 in the post-reform period and a total count of 447 articles. The split of the two coauthored articles which fall into the post-reform period increases the number of distinct authors in that period to 95 and the total number of distinct authors in all periods to 163.

We are interested in citation pairs that connect scientists who lived in Great Britain in the publication year of the respective article. This means we can restrict our search to articles that were written by authors who resided in Great Britain in the publication year(s) of their article(s). Table [B11](#) zooms in on these articles. The coauthored articles are already split up in table [B11](#). Table [B12](#) displays summary statistics for all citations in these articles.

The citation counts in table [B12](#) are restricted in the following way. Total citations: all citations we have entered. Regular citations: citations excluding references to military and other personnel who conducted measurements and are only listed in the tables that display these measurements. Citations to living scientists: citations to scientists who were alive in the publication year. Citations to geolocated

Table B10:
 Articles in the *Philosophical Transactions* in the observation period

Period	Articles	Pages	Article length	Authors	Articles per author	Pages per author
1830	26	419	16.12	20	1.30	20.95
1831	28	495	17.68	18	1.56	27.50
1832	26	599	23.04	17	1.53	35.24
1833	29	811	27.97	24	1.21	33.79
1834	29	582	20.07	23	1.26	25.30
1835	21	356	16.95	18	1.17	19.78
1836	26	605	23.27	20	1.30	30.25
1837	24	430	17.92	19	1.26	22.63
1838	20	399	19.95	13	1.54	30.69
1839	22	420	19.09	16	1.38	26.25
Pre period	251	5116	20.38	99	2.54	51.68
1840	24	604	25.17	20	1.20	30.20
1841	21	297	14.14	16	1.31	18.56
1842	15	300	20.00	15	1.00	20.00
1843	14	327	23.36	13	1.08	25.15
1844	12	319	26.58	13	0.92	24.54
1845	17	357	21.00	13	1.31	27.46
1846	29	626	21.59	22	1.32	28.45
1847	17	251	14.76	12	1.42	20.92
1848	19	269	14.16	17	1.12	15.82
1849	24	507	21.13	20	1.20	25.35
Post period	192	3857	20.09	93	2.06	41.47
Total	443	8973	20.26	161	2.75	55.73

Table B11:
Articles by Authors who lived in Great Britain in the Publication Year

Period	Articles	Article share	Pages	Page share	Article length	Authors	Author share	Articles per Author	Pages per Author
1830	21	80.8	358	85.4	17.0	17	85.0	1.24	21.1
1831	24	85.7	408	82.4	17.0	16	88.9	1.50	25.5
1832	22	84.6	560	93.5	25.5	17	100.0	1.29	32.9
1833	26	89.7	791	97.5	30.4	24	100.0	1.08	33.0
1834	25	86.2	490	84.2	19.6	22	95.7	1.14	22.3
1835	17	81.0	288	80.9	16.9	15	83.3	1.13	19.2
1836	23	85.2	533	86.9	23.2	20	100.0	1.15	26.7
1837	21	87.5	405	94.2	19.3	18	94.7	1.17	22.5
1838	19	95.0	358	89.7	18.8	13	100.0	1.46	27.5
1839	20	90.9	394	93.8	19.7	16	100.0	1.25	24.6
Pre period	218	86.5	4585	89.5	21.0	89	89.9	2.45	51.5
1840	21	84.0	521	86.3	24.8	19	90.5	1.11	27.4
1841	21	100.0	297	100.0	14.1	16	100.0	1.31	18.6
1842	14	93.3	266	88.7	19.0	14	93.3	1.00	19.0
1843	13	92.9	291	89.0	22.4	13	100.0	1.00	22.4
1844	11	84.6	317	93.8	28.8	11	84.6	1.00	28.8
1845	13	76.5	309	86.6	23.8	13	100.0	1.00	23.8
1846	26	89.7	594	94.9	22.8	22	100.0	1.18	27.0
1847	13	76.5	222	88.4	17.1	12	100.0	1.08	18.5
1848	16	84.2	224	83.3	14.0	16	94.1	1.00	14.0
1849	23	92.0	470	92.7	20.4	20	95.2	1.15	23.5
Post period	171	87.7	3511	90.6	20.5	88	92.6	1.94	39.9
Total	389	87.0	8096	90.0	20.8	150	92.0	2.59	54.0

Table B12:
Citations by Authors who lived in Great Britain in the Publication Year

Period	total citations		regular citations		to living scientists		to geolocated scientists		to scientists in Great Britain	
	count	count	share	count	share	count	share	count	share	
1830	147	146	99.3	101	69.2	100	99.0	60	60.0	
1831	170	166	97.6	91	54.8	88	96.7	44	50.0	
1832	268	253	94.4	163	64.4	154	94.5	80	51.9	
1833	405	404	99.8	245	60.6	216	88.2	98	45.4	
1834	209	209	100.0	118	56.5	115	97.5	56	48.7	
1835	201	201	100.0	135	67.2	132	97.8	52	39.4	
1836	291	218	74.9	144	66.1	143	99.3	75	52.4	
1837	202	200	99.0	120	60.0	120	100.0	72	60.0	
1838	175	175	100.0	90	51.4	89	98.9	35	39.3	
1839	209	209	100.0	152	72.7	151	99.3	73	48.3	
Pre period	2,277	2,181	95.8	1,359	62.3	1,308	96.2	645	49.3	
1840	255	255	100.0	192	75.3	190	99.0	67	35.3	
1841	201	199	99.0	142	71.4	140	98.6	64	45.7	
1842	147	146	99.3	108	74.0	108	100.0	57	52.8	
1843	146	145	99.3	114	78.6	114	100.0	50	43.9	
1844	144	144	100.0	95	66.0	95	100.0	51	53.7	
1845	78	77	98.7	61	79.2	60	98.4	28	46.7	
1846	310	309	99.7	212	68.6	209	98.6	91	43.5	
1847	102	101	99.0	53	52.5	53	100.0	25	47.2	
1848	128	128	100.0	97	75.8	94	96.9	53	56.4	
1849	219	219	100.0	178	81.3	169	94.9	88	52.1	
Post period	1,730	1,723	99.6	1,252	72.7	1,232	98.4	574	46.6	
Total	4,007	3,904	97.4	2,611	66.9	2,540	97.3	1,219	48.0	

scientists: citations for which we were able to find the locations of the author and the cited scientist. Citations to scientists in Great Britain: citations that connect two scientists who resided in England, Wales, or Scotland in the publication year of the article which contains the citation. The bases of the percent shares are the following: regular citations: total citations, citations to living scientists: regular citations, citations to geolocated scientists: citations to living scientists, citations to scientists in Great Britain: citations to geolocated scientists.

E.2 Identifying and Locating Authors and Cited Scientists

To identify cited scientists, we used their name and title as well as information about the type of work they were involved in as revealed by the article in which they were cited. Given this information, a team of trained research assistants conducted a systematic review of biographical information in order to uniquely identify the cited scientists. The most important resources used in this review were the fellows directory of the Royal Society, the *Oxford Dictionary of National Biography*, and the *Catalogue of Scientific Papers*. If none of these resources allowed us to uniquely identify the full name of the scientist, we then turned to other approaches, such as conducting Google searches for other web-based resources which could then be compared to the available information on the scientists work, as described in the citing article. These biographical resources were used to identify the primary location of the author or cited scientist in each year in which they either published an article or were cited in an article.

Some of the additional data sources used to identify and locate scientists are listed below:

- Poggendorff's (1863) dictionary of scientists concisely states the vita of each included scientist. Location information can be extracted directly from the institutions that are listed in a scientist's vita. The dictionary is comprehensive and the coverage particularly good for scientists from Continental Europe.
- Several directories and lists covering specific professions were used. These include Clifton's (1995) directory of British scientific instrument makers, O'Byrne's (1849) dictionary of officers in the Royal Navy, and British Almanacs (1828-1875) which list all university professors in the UK.
- We also referred to the *Catalogue of Scientific Papers*, which lists virtually all scientific articles that were published between 1800 and 1860.