A road for Prometheus: Technological disruptions and infrastructure investments in history

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A ROAD FOR PROMETHEUS
TECHNOLOGICAL DISRUPTIONS AND INFRASTRUCTURE INVESTMENT IN HISTORY

Tommy E. Murphy*

ABSTRACT

This article reviews some of the literature on technological disruption and infrastructure investment over the long run, looking at how service provision was affected by that interaction. Although less common in pre-industrial times, since the Industrial Revolution technology 'disruption' has been a regular feature. There are no reasons to think it will be different this time around. Evidence suggest these technological changes tend to be positive in the long run, but the short-term distortions they generate tend to create a series of anxieties and opposition. Because of this, part of the society will be negatively affected, will oppose change, and could delay adoption of otherwise welfare-enhancing advancements. This is particularly important when technological improvement interacts with infrastructure, as government involvement and regulation could play a major role to make the transition smooth, or even possible.

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1. INTRODUCTION

What is probably the most beloved tale of the author that epitomises the genre of 'science-fiction-that-became-true' has, in fact, nothing to do with science fiction; it's all about how new, but existent technology changed infrastructure and the services provided around that infrastructure. The 'world' in *Around the World in 80 Days* was the one Jules Verne was witnessing when writing the novel; a world full of marvels. Just a few years before its publication in 1873, things like the first communication between North America and Europe using the transatlantic telegraph cable (1858), the completion of the First Transcontinental Railroad in America (1869), the linking of the Indian railways across the subcontinent (1870), or the opening of the Suez Canal (1869) had suddenly made the world considerably smaller. The remarkable voyage of Phileas Fogg and Passepartout was, at the time of Verne's writing, certainly *not* science fiction. Just a few years later, in 1889, the famous journalist Nellie Bly would actually do Fogg's trip –visiting Verne in the way– in just 72 days [Bly, 2015 (1890)]. It is understandable, however, that to the larger part of the population these new developments *seemed* science fiction. Many of the 'things' that allowed Fogg to win his wager, mostly transport and communication services, were entirely unknown a generation before. A combination of relatively novel technologies (such as steam machines put on wheels or boats) and large infrastructure investments (including channels, railways, and bridges) had changed how many of these services were provided, altering the way in which things were done. Something worth telling a story about.

Although it seems quite natural to think that shocks to infrastructure can have a major impact on people's lives, it is certainly far from obvious. In fact, in the seminal and iconoclast study that was going to pave his road to the Nobel prize, Robert Fogel suggested railways –perhaps the greatest nineteenth century infrastructure project– contributed only marginally to the American growth [Fogel, 1964]. But there is ample evidence now that –at least in general– infrastructure, and the services provided with it, do have a positive effect on society. On the most basic level, it directly affects costs and productivity. Developments in transport and communication services also contribute to market integration, which allows people to benefit from comparative advantage by fostering division of labour [see e.g. Donaldson, 2018]. Projects that improve energy provision or water treatment can have substantial effects on health and standards of living. And the impact of infrastructure is certainly not circumscribed to contemporaneous effects. In an extreme case of long-term effects, Daagart *et al.* [2018] document how areas that attained greater road density during Roman times are characterised by a significantly higher road density, and prosperity, *today*. This kind of results suggest infrastructure maybe one important channel through which the persistence in comparative development (and underdevelopment) comes about, making investment in infrastructure particularly relevant for policymakers. In an eloquent illustration of this, Voigtländer and Voth [2017] discuss how Hitler gained substantial support following the construction of the Autobahn, one of the most important projects of Hitler's government, intended to reduce unemployment, and widely used for propaganda purposes. Studying data on motorway construction and the 1934 plebiscite, which gave Hitler great powers as head of state, the authors show road building was highly effective in reducing opposition to the nascent Nazi regime.

Technological change is also crucial for economic progress. As the prominent economic historian Joel Mokyr put it, technological progress "*has been one of the most potent forces in history in that it has provided society with* [...] *an increase in output that is not commensurate with the increase in effort and cost necessary to bring it about*" [Mokyr, 1990: 3]. In a context of limited resources, technological innovation is the *only* way of achieving

long-term growth, and the last two centuries are a vivid illustration of this. Since the Industrial Revolution there were major breakthroughs in manufacturing, agriculture, transportation, energy production, and medical services, to name a few. The pace of technological change has grown exponentially and standards of living have accordingly accompanied that growth, in terms of income per capita, real wages, heights, or calorie consumption [see, e.g., Floud *et al.*, 2011].

And, of course, technology and infrastructure are interlinked. Available infrastructure may determine the direction of technological progress and many technological innovations require a particular infrastructure or change the way in which we use that infrastructure. Substantial changes in one or another hence hold the potential of having a disruptive effect on society. And there seems to be a growing consensus that we are now about to embark in a transformation as disruptive as the one influencing Jules Verne's time, especially in transport and energy. For Baldwin [2016], for example, current globalisation driven by fast-paced technological change and production fragmentation is more sudden, more individual, more unpredictable, and more uncontrollable. Most of the headlines these days centre on a few innovations related to transportation such as electric cars, autonomous vehicles, and drones. The energy sector is also expected to be affected by the increased efficiency of alternative sources (e.g. solar or wind power), as well as by the improved capabilities of storing devices. No major change is at the moment foreseen in communication technologies, yet the expansion of the currently available networks and the construction of new business models around them –the 'uberisation' of different markets– is indeed expected to be disruptive as well.

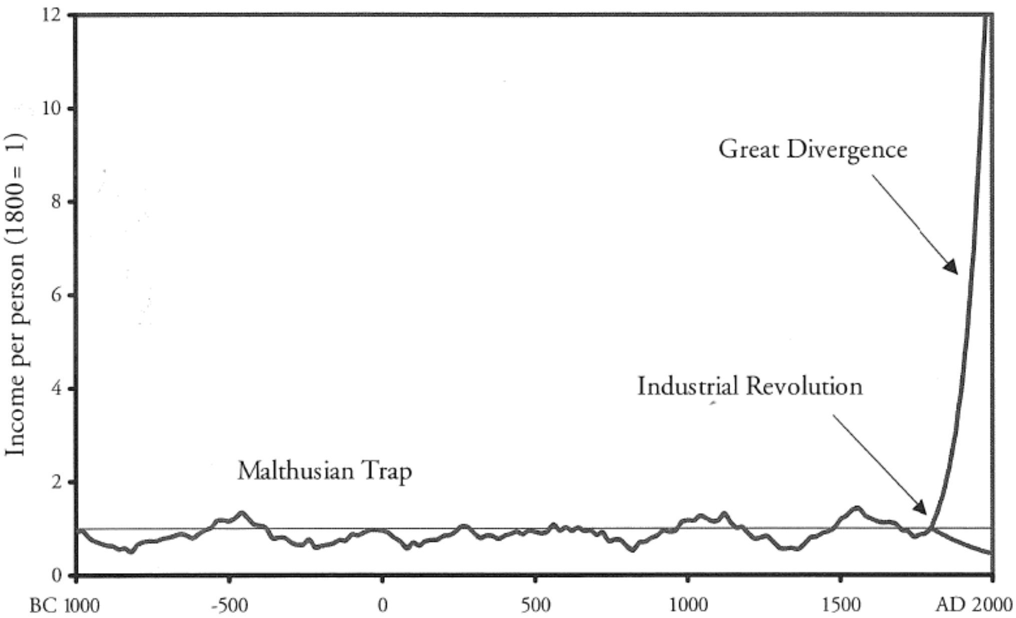
Uncertainties related to the potential development of new technologies, and how they are received by the public, normally generate anxieties. As infrastructure is so intimately related to many of them, and could play a crucial role in fostering or discouraging their adoption, those anxieties are understandably exacerbated. But, how much of this is really new? Are we facing a paradigm change or just another iteration of a now regular process? This article reviews some of the literature that discuss the role of technological disruption and infrastructure investment in history, paying attention to how service provision was affected by their interaction. It suggests that, indeed, if we look at the very long term, the pace of technological change has certainly accelerated, but since the Industrial Revolution technological disruptions of some sort have become a somewhat regular feature. Each disruption is of course different, but some general patterns can be identified on how they affect society in general, and different groups within that society.

2. INFRASTRUCTURE AND TECHNOLOGY AND GROWTH

As far as we know, for the major part of human history, few things really changed in terms of how well people lived. Data conveying this sort of information is needless to say hard to get, but the general picture drawn by various indicators is surprisingly consistent. Up until about two hundred years ago the standards of living somewhat varied from one society or period to another, but there was no general long-run trend. There were of course some people doing better in the late middle ages than in ancient Rome, but the average person was most likely no better, living very close to subsistence. Yet sometime around 1800 this changed, and an era of unseen growth and prosperity began, at least for a considerable part of the world population. This 'hockey-stick' pattern of long-run stagnation (the shaft of the stick) with a recent, sudden outburst of growth (the blade) is generally associated with the income per person graph by Clark [2007] reproduced here in Figure

1, but can be replicated with several alternative proxies of standards of living, such as real wages, population growth or urbanisation, anthropometric measures (e.g. human heights), or life expectancy. Its main message is that income per capita seems to have remained at subsistence level for a very long time, a period sometimes known as the *Malthusian Trap*, with improvements (if any) in the standard of living only marginal or temporary. Then, barely two centuries ago, this ceased to be the case, and –following an *Industrial Revolution*– an era of sustained growth began in some regions of the world. The fact that this incredible growth upsurge did not materialise in *all* regions led to what is now normally referred to as the *Great Divergence* of income. Although many details are still debated, it is generally agreed upon that technological progress is central to understand the last two stages of these stylised facts. Modern economic growth during the Great Divergence is largely driven by constant technological change, and the increased rate of innovation is one of the most salient features of the Industrial Revolution.

Figure 1. Income per person, 1000 BC to AD 2000



Source: Clark [2007: 2]

Smithian growth in pre-industrial times

Innovations did spring up and spread in the pre-industrial period too. This, however, took place at a slower pace and –most likely due to subsequent demographic, 'Malthusian' pressures– their impact on society was typically short-lived. Different innovations in sectors like shipping or metallurgy would give Europe its military advantages [Diamond, 1997], but in largely agricultural societies, like the ones in those times, most of the innovations with the greatest impact on people's welfare were connected to the work in the fields. In the middle ages, Europe witnessed the spread of the water-mill, the heavy plough, the crop rotation system, and the horseshoe, to name a few. Many of these appeared in other parts of the world, but Europeans were particularly capable of adapting these inventions for different activities. The mill, which probably originated in Asia in the seventh century, is a good example of a technology initially applied to a particular purpose (milling cereal), that expanded to infinite uses in Europe. In sixteenth century Holland windmills were used to produce textiles (to spin cotton or full cloth), gunpowder, oil, saw

wood and drain water [Malanima, 2009: 76]. The water wheel was used to produce beer at least since 861 in France, iron since 1025 in Germany, and paper since 1276 in Northern Italy [Cipolla, 1994: 141]. Wind and water provided some of the energy needed to use machines, but the main source of energy for mechanical work in the pre-industrial time was biological, coming directly from animals and humans. Here many innovations also appeared. Along with the introduction of the horseshoe, for example, there were new methods of harnessing draft animals and selected breeding of horses, both fostering the replacement of oxen by horses, which were stronger and faster animals. Most importantly, horses also increased substantially the speed of land transportation, which was generally carried out in poorly maintained roads. Modernisation in agriculture, however, tended to be slow. All kind of innovation typically involves high costs of research and development (mostly time), its returns are unpredictable, and –since new technologies behave like public goods– in absence of a figure capable of dealing with the appropriability problem (like the state), the market usually ends up producing too few of them. But the agricultural sector holds additional problems. Typically, the times needed to produce agricultural goods are too long, making research and development particularly costly. Often, innovation needs to be adapted to local condition of weather or soil characteristics. The fact that knowledge acquisition and reproduction in pre-industrial times was not systematic enough also raised a series of problems. On the one hand, before the Enlightenment there was not a clear connection between science and technology, and most discoveries came from trial and error, which is a highly irregular way of acquiring knowledge. Science would not lead to the discovery, but *follow* serendipitous breakthroughs. On the other, since knowledge tended to be imbedded in people (e.g. a skilful craftsman and his apprentice), demographic shocks like plagues and lethal epidemics, which were frequent at the time [Alfani and Murphy, 2017], led to the occasional disappearance of the acquired knowledge.

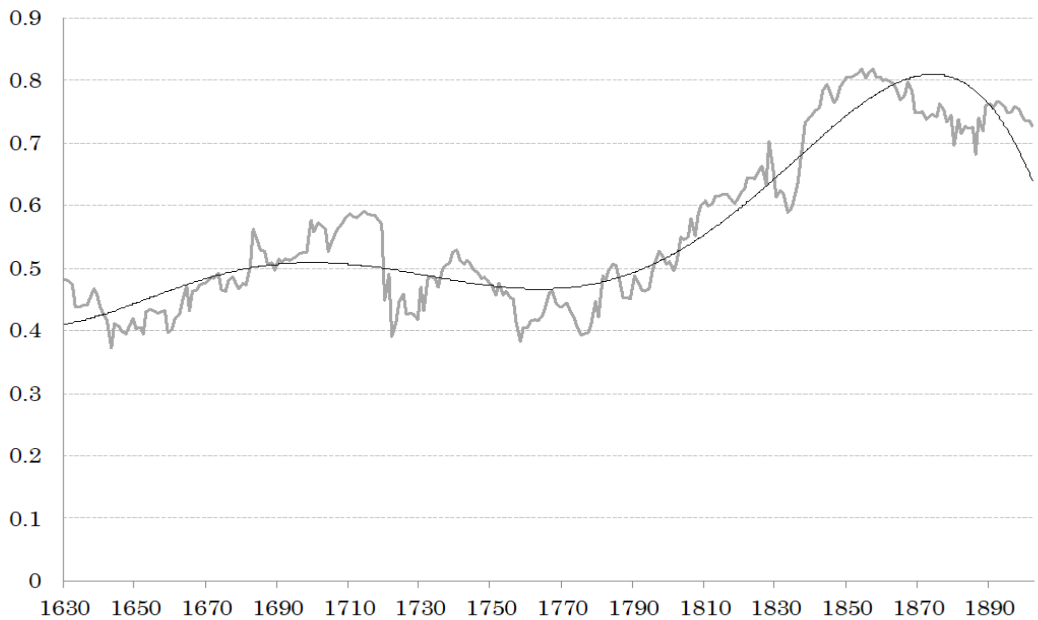
Economic growth can come from many different sources, but its most immediate explanations are either factor (e.g. capital or labour) accumulation or technological innovations [Acemoglu *et al.*, 2005], and it is clear that only the latter are capable of producing long-term growth. But the actual nature of these innovations is important to understand their dynamics. Nowadays we are most familiar with the idea that innovations result from entrepreneurial investments in research and development, probably connected to scientific efforts, and motivated by the prospects of obtaining monopoly rents. Some scholars [e.g. Mokyr, 1990] call growth coming from this process *Schumpeterian growth*, in honour of the Austrian political economist who pointed out that innovations imply this replacement of the old technologies by the new and, hence, creative destruction. As the above discussion suggests, this kind of growth was not the one pushing the technological frontier in pre-industrial times and, in fact, it will have to wait till the Industrial Revolution to gain a major relevance. Most of the economic growth before then was really *Smithian growth*. That is, improvements coming from individuals and groups engaging in trade and, in doing so, becoming better at producing what they produce thanks to specialisation, as emphasised famously by Adam Smith.

It is in fact interesting to note how relevant was the role of infrastructure and the services around that infrastructure for these latter forms of growth in pre-industrial times. In a period with only occasional improvements in actual technology, a large part of efficiency improvements would come from division of labour and eventual learning by doing. But for this to materialise, expansion of trade is crucial. Since the seminal works of North [e.g. North, 1990] a great deal of the attention has been put into how institutions achieved this. Banking practices, periodic fairs, or private-order contractual enforcement

institutions have all contributed to the development of long-distance trade [North and Thomas, 1973; Greif, 2006]. Institution might as well be the ultimate source of growth [Acemoglu *et al.*, 2005], but the immediate sources involved improved infrastructure that provided a greater capacity to channel energy (as discussed with the case of wind and water mills) or move from one way to another. Some technological advancements in shipping were important, as well as the spread of tools like the compass and nautical maps. But the great majority of exchanges were still governed by the transportation costs of internal overland traffic and most of the pre-steam developments in this traffic were in infrastructure, not technological changes *per se.* In England and Wales, for example, road surfaces and gradients were improved and the inland waterway network expanded [Alvarez-Palau *et al.*, 2017]. Improved transportation in particular stimulated market integration at least since early modern period, fostering Smithian growth [Studer, 2015].

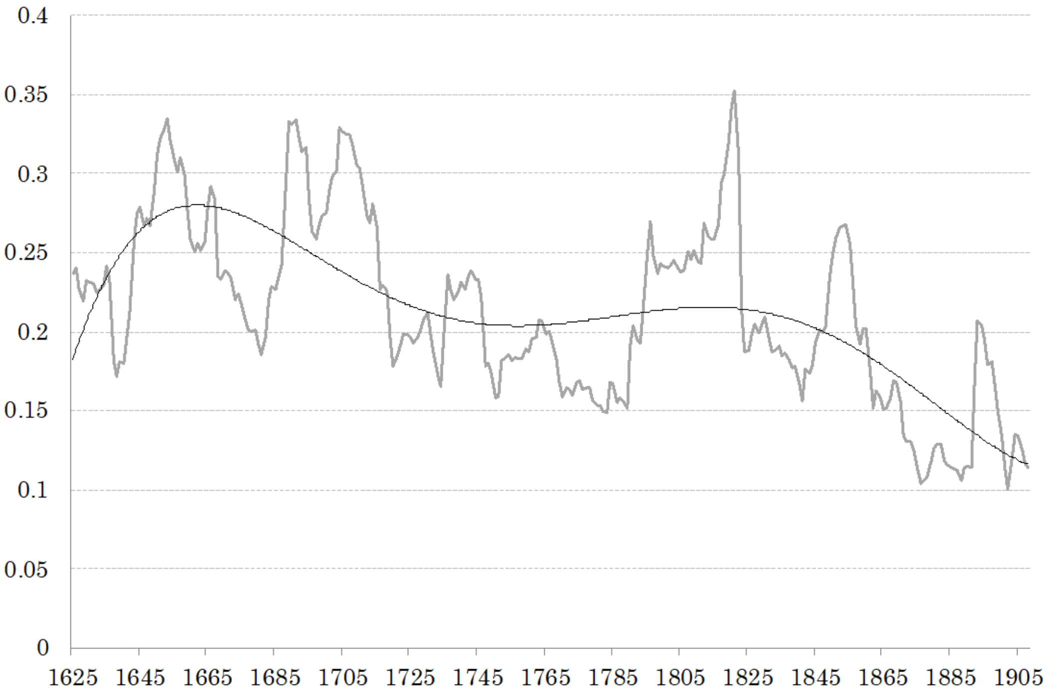
There are many ways of illustrating how Smithian forces were at play in pre-industrial times, but the require us to dig deeper into the theoretical implications of market integration. Most of the literature on this subject is based upon the rather intuitive idea that when traders share information and trade costs are small, price differences are quickly arbitraged away and prices converge. When this happens, one can say that two or more markets are integrated. And, because of arbitrage, prices between integrated markets develop stable relationships; that is, they become highly correlated, they move together. Also, the efficiency with which of markets function in terms of operations affects price volatility in individual localities: the more efficient the markets, the better protection from local shocks (such as a bad harvest), so prices become stable. Co-movement of prices in two locations, and stability of prices in one location are two easily testable hypotheses. Obtaining an actual figure for these relationships is quite challenging, but Chilosi *et al.* [2015] used information prices of wheat, a rather homogeneous good, for several European cities and assessed the co-movements of each pair of cities and the volatility of the series, which is shown in Figures 2 and 3.

Figure 2. Co-movement of wheat prices in Europe: Average 21-years rolling correlation coefficient, 1630-1902



Source: Adapted from Chilosi *et al.* [2015]

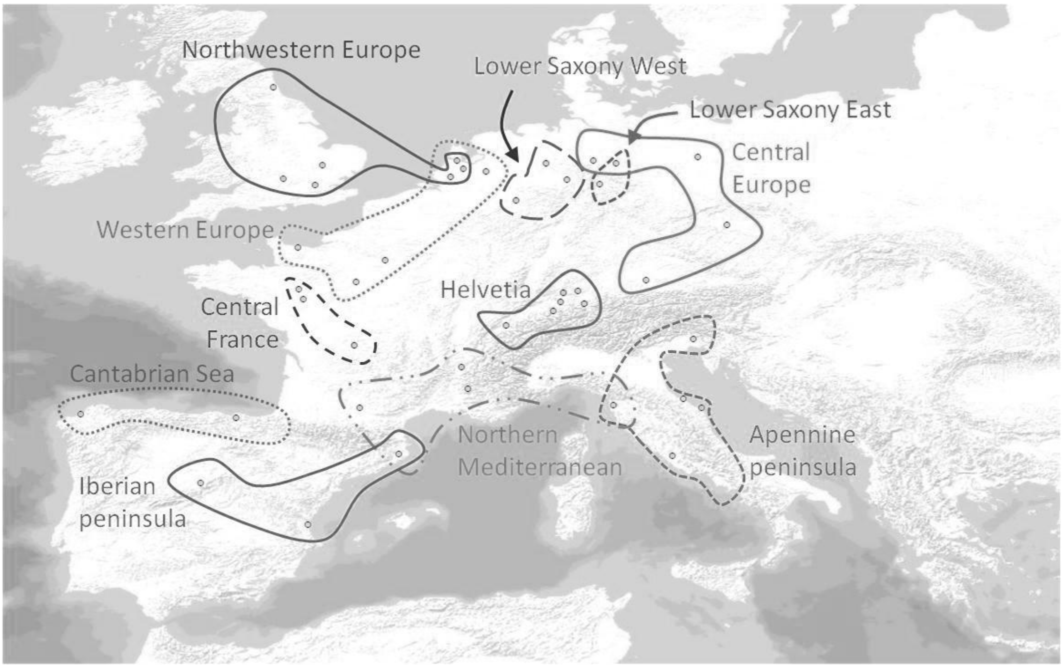
<u>Figure 3</u>. Volatility of wheat prices in Europe: Average 11-years rolling coefficient of variation, 1625-1908



<u>Source</u>: Adapted from Chilosi *et al.* [2015]

Although modest, one can easily see in both graphs a trend towards greater integration. In the long run, this is more clearly seen with the decreasing volatility of prices. But the co-movement of prices also shows a similar trend, with an eventual take-off in the mid-eighteenth century. During this period, before the Industrial Revolution, relatively distant markets were behaving as one, as shown in Figure 4. Here Chilosi *et al.* [2015] use a slightly more sophisticated tool called principal component analysis, a popular analytical technique to classify variables according to patterns of co-movement to 'let the data talk' and identify regions that behave as single markets. That is, it tries to recognise which sets of prices behave as if they were belonging to the same market. Here it is interesting to see how relatively distant places like northern England and the Netherlands are apparently part of the 'same' market.

Figure 4. Wheat markets in Europe, 1715-1789



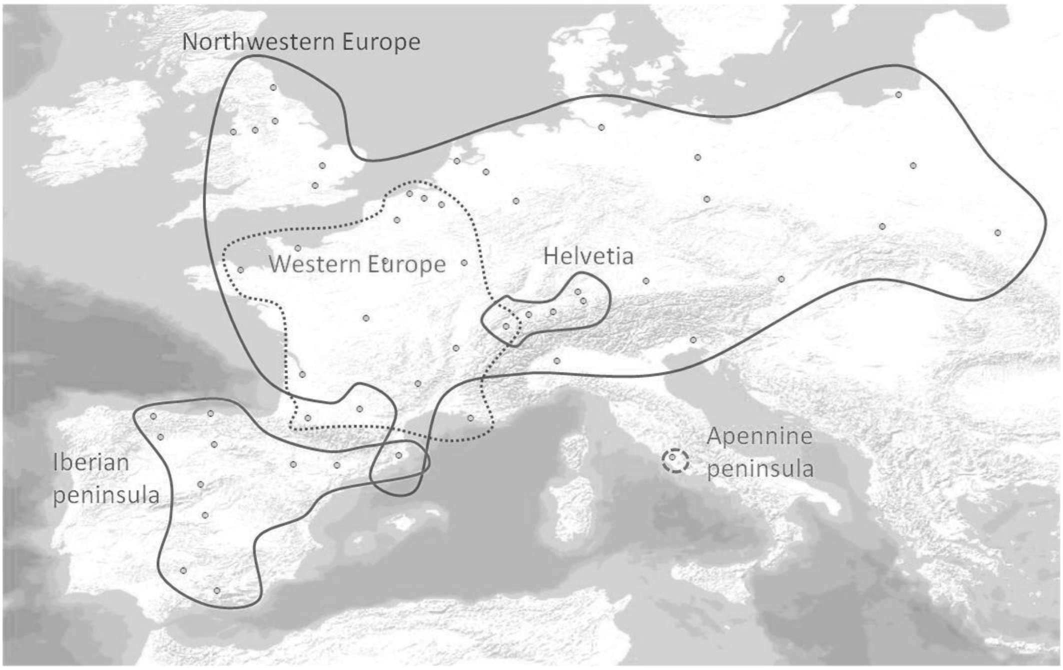
Source: Chilosi *et al.* [2015]

It is of course hard to say which actual factor contributed to this process of integration, but given that transport costs were such a binding constraint in the period, improvements in infrastructure and transportation probably mattered a lot. As pointed out before, a great deal of the attention has been put into how institutions contributed to the performance of early modern economies [North and Thomas, 1973; Greif, 2006]. But some authors, most notably Bogart [e.g. 2005, 2014], have made the point that one of the channels through which institutions mattered for development was indeed how local institutions were able to provide the right environment to generate public goods (such as infrastructure) that increased efficiency. Rosenthal [1990], for example, provided evidence that only when the French Revolution enacted reforms that changed the costs of securing property rights (that is, changed the institutions) in Southern France did irrigation projects (infrastructure) began to be developed. In a context of growth dynamics dominated by Smithian (and not Schumpeterian) growth, things that reduced transport costs were of outmost importance. At least in the transport sector, institutions have been crucial to explain the extent and quality of infrastructure networks such as channel developments or turnpikes [Bogart, 2019].

Changing gear

Something clear from Figure 1 is that, after 1800, at least some things *were* different. Closer inspection of Figures 2 and 3, which include the period around 1800, highlights how important was this to foster integration. The modest improvements we identified in the seventeenth and eighteenth centuries gain substantial momentum. The large, but isolated local markets of Figure 4 now become a large European market in Figure 5 in the nineteenth century. A major shift took place between early modern and nineteenth-century Europe, whereby regional markets gave way to continental-wide markets in the latter period. This is hardly surprising, as one sector particularly affected by the Industrial Revolution was transportation.

<u>Figure 5</u>. Wheat markets in Europe, 1835-1900



<u>Source</u>: Chilosi *et al.* [2015]

Although no other single event has been more studied in economic history, the Industrial Revolution still generates hotly debates. Was there an actual 'revolution'? How big was it? Why? Why then? Why England? None of these questions seems to have found an entirely satisfactory answer in the literature, but the discussion has generated endless interesting insights, some of which are useful for the discussion here.

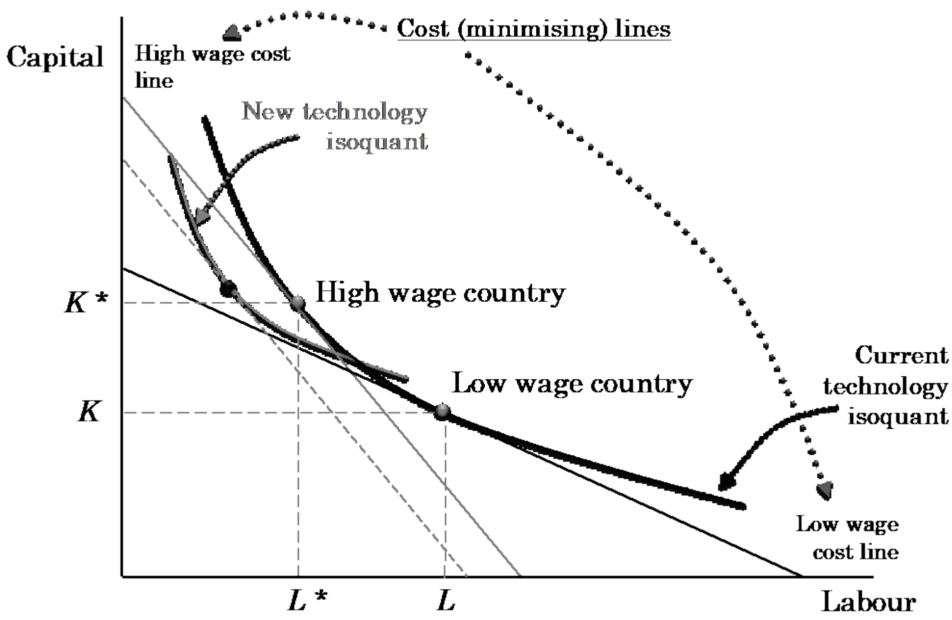
One of these insights is that, if there was ever something that could be referred to as a 'disruption', as it is evident from Figure 1, this was it. The magnitude and timing of this disruption, however, has been one of the most hotly debated issue and the stand one could take on the discussion depends a lot on what one is actually looking at. Estimates of national income per capita concur on low rates of annual growth in the early eighteenth century (between 0.4% and 0.3%) and high rates in the second part of the nineteenth century (about 2%), but where some see an abrupt change around 1800, others see just an acceleration [Mokyr, 1999: 11]. When looking at industrial production, rates are higher, but the story similar. For historians of technology, however, the idea of discontinuity is less controversial. Quantitative analyses of patent statistics suggest a sharp increase in the late 1750s, whereas non-quantitative approaches illustrate with the myriad of technological innovations that sprung between 1760 and 1860 (e.g. the steam engine, the spinning jenny, coke smelting) the same point [Mokyr, 1999: 8-9]. Productivity in specific sectors increased rapidly. Harder to measure, but also relevant were the constant marginal improvements in production that made many objects better and cheaper. Adam Smith never mentioned some of the later most famous innovations of the eighteenth century, but did point out how watches had become much cheaper. A recent study took that cue and, using records from reports on stolen watches, studied the evolution of watches' prices between 1685 and 1810, showing that these innovations contributed to a fall of nearly 75% in their prices [Kelly and Ó Gráda, 2016].

This takes us to another crucial point: the change in the nature of technological innovation. As pointed out earlier, good part of advances in the pre-industrial era were coming from Smithian growth, in good part driven by institutional changes or improvements in infrastructure. Schumpeterian growth was not entirely absent, but it was largely depending on trial and error. This changes dramatically around this period. The pace of technological change speeds up in part because the way in which new technology appears also changes. Why this happened is not entirely clear. Joel Mokyr, for example, has historically championed the idea that this change was supply-driven in the sense that the supply of new ideas changed, thanks to diverse factors, but most importantly by the industrial enlightenment. A largely European phenomenon, Enlightened culture and institutions created an environment supportive for inventions [Mokyr, 2007]. Under the influence of thinkers like Francis Bacon or Isaac Newton, it begins to appear the idea that nature could be understood through systematic research and hence controlled, opening the door for science-based knowledge. At the same time, the cost of accessing knowledge decreased, thanks to the increasing literacy and appearance of academies, scientific societies or the first encyclopaedias. Institutions that protected intellectual property rights like patents also increase during this period. Good government also probably helped. Glorious Revolution of 1688 that consolidated parliamentary ascendancy, minimal government, and secure property rights [North and Weingast, 1989], probably fostered investment in research and development.

But another line of work that recently has gained substantial support is one that, while recognising the importance of institutions and culture to foster technology supply, emphasises the role of technology demand. Most notably Allen [2009a] has argued that research and development are a response to incentives, and these changed in Britain during the period. The 'wave of gadgets that swept through England', as famously put by Ashton [1955], were a consequence of the relative prices of factors. English high wages, most likely stimulated by the growing Atlantic economy, and cheap coal created a demand for labour-saving, energy-using technology. Allen developed this story more eloquently looking at the case of the Spinning Jenny, the machine that displaced the spinning wheel (the one that infamously put the 'Sleeping Beauty' to sleep) from the English landscape [Allen, 2009b]. Since in England wages were exceptionally high relative to capital prices, a machine that would save in the use of labour was profitable. But since that made it only profitable in Britain (were labour was particularly expensive), that was the only country where it as worth investing in its development. The main logic of the argument is illustrated in Figure 6. The 'current technology isoquant' indicates the combination of labour and capital that can produce a particular level of output given the available technology. Since different countries or regions may face different prices for those inputs, they will choose different points in this isoquant. In a 'low wage country' the cost line is flatter (because labour is cheap), so a cost minimising firm will hire many workers and use relatively little capital (L, K). Since in the 'high wage country' that cost line is steeper (because labour is expensive), entrepreneurs find it profitable to replace some of the workers with capital, finding an equilibrium in (L*, K*). Between 1630 and 1830 the price of capital relative to labour systematically increased in Britain, while remaining stable in other places of Europe, like France [Allen, 2009b: 911]. This means that even if both countries started in similar places in the seventeenth century, during the following period England was looking more and more like (L*, K*), while France was remaining in (L, K). But this created not only an incentive for England to become capital intensive, but also to invest the time and money needed for the research and development technologies that used even more intensively capital. That is, fostered Schumpeterian growth. The 'new technology isoquant' shows precisely this biased (towards capital) technological change. The

Spinning Jenny, the mule, and many other inventions of the period used relatively much more capital per labourer than any of the previous technologies did.

Figure 6. Capital, labour and biased technological change

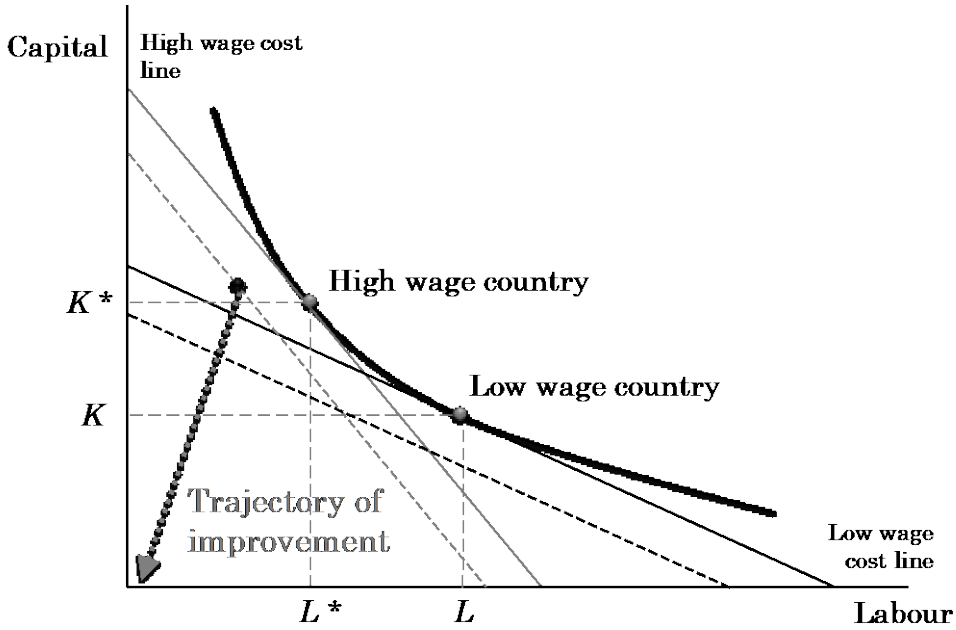


Source: Adapted from Allen [2011]

Now, Figure 6 points out another important potential feature of biased technological change: this new technology *will not* necessarily be used in the low wage country, even if it is costless to replicate. Notice that given the relative price of labour with respect to capital, it is still more efficient to use loads of cheap labour in the old technology than to switch to the new (capital intensive) technology. This country will switch to the only under two circumstances. The most obvious is, of course, if the wage cost line flips, because capital becomes relatively cheaper or wage relatively expensive. Things like secular changes in wage levels driven by demography or human capital accumulation, or the discovery of natural resources could lead to this sort of dynamics. But they might also switch to the capital-intensive technology if it improves over time, as shown in Figure 7. As the new technology becomes more efficient, the production function moves up, so the isoquants move down: one can produce more with relatively less capital and labour. If this continues (following the trajectory of improvement, which is now more capital-intensive), there might come a time in which it will pay for the entrepreneurs in the low wage country to replace the old technology with the new. This brief discussion highlights the critical fact that innovation does not imply adoption. Rational agents will refrain from adopting technologies that are available but not profitable, as they use too much capital (physical or human) that might be too costly. Allen elaborates an extensive description of how the Spinning Jenny was not adopted in India and France. The case of France is particularly eloquent because it was a real possibility there, just across the channel. "*The French aversion to jennies was not due to lack of knowledge; indeed, the French government actively promoted them*" [Allen, 2009b: 914]. Why, Allen asks, were the French unenthusiastic about the jenny? He is quick to disregard diverse institutional and cultural explanations because most of them *assume* profitability of adopting the new technology was the same in England and France. But this was simply *not* the case. Given labour and capital costs, Allen estimated that the rate of return to buying a Spinning Jenny in England was about 38%, while in France barely 2.5%. "The purchase of a jenny absorbed half a year's

earnings in Britain and a year and a half's earnings in France. Purchasing a jenny represented such a large commitment that modest people may have expected an exceptional return" [Allen, 2009b: 917]. And 2.5% was not that exceptional.

Figure 7. Technological improvement

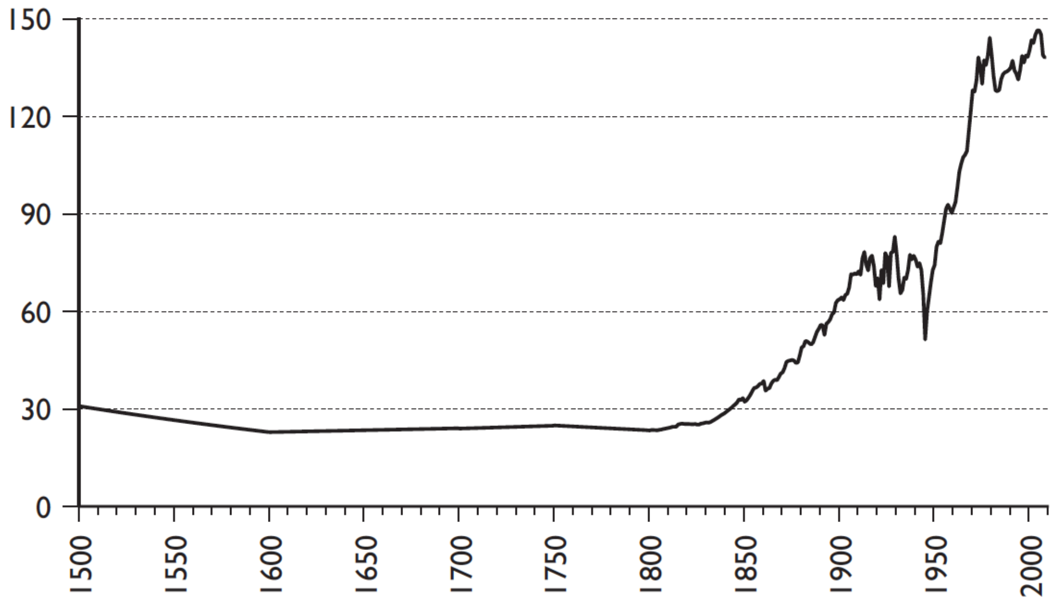


Source: Adapted from Allen [2011]

Although highlighting different mechanisms, supply and demand stories are of course not incompatible or inconsistent with each other, and both can contribute to explain why the nature of technological change became somewhat different since the late eighteenth century.

An element that clearly played a role in the transition to this new pace of technological change was that some specific innovations during the Industrial Revolution had a major, disruptive impact in the way of harnessing of energy. The incredible economic progress of the last two hundred years could not have been achieved without greater access to energy, which in pre-industrial times placed a serious limit to growth. These new technologies opened up the use of "energy carriers" that were inaccessible before but had only been used marginally (e.g. coal, oil, or natural gas), as well as entirely new sources (such as electricity) [Kander *et al.*, 2013]. As Figure 8 shows, consumption of energy consequently exploded, thanks to the fact that energy became increasingly cheap.

<u>Figure 8</u>. Energy consumption per capita in Europe, in gigajoules, 1500-2000



<u>Source</u>: Kander *et al.* [2013: 5]

A well-documented example of how this new access to sources of energy had an impact on society is that of lighting, elaborated some time ago by the recent Nobel laurate William Nordhaus. He was trying to make a seemingly obvious, but subtle and crucial point: that during periods of great technological change building price indexes that capture the impact of new technologies on standards of living is very difficult. Most of the things we consume now were simply not produced in the past:

> "*We travel in vehicles that were not yet invented that are powered by fuels not yet produced, communicate through devices not yet manufactured, enjoy cool air on the hottest days are entertained by electronic wizardry that was not dreamed of, and receive medical treatments that were unheard of. If we are to obtain accurate estimates of the growth of real incomes over the last century, we must somehow construct price indexes that account for the vast changes in the quality and range of goods and services that we consume, that somehow compare the services of horse with automobile, of Pony Express with facsimile machine, of carbon paper with photocopier, of dark and lonely nights with nights spent watching television, and of brain surgery with magnetic resonance imaging.*" [Nordhaus, 1996: 29-30]

Since these changes in quality and range are rarely incorporated in traditional price indexes, using them overstate the increase in the price of many products, hence understating the impact on standards of living. Nordhaus picks the case of lighting to make his point. He collects information on lighting efficiency of different sources of lighting to construct a 'true' price of light, and shows it is quite low compared with standard prices. To do this exercise, Nordhaus pieces together a history of lighting he summarises in a table reproduced, slightly modified, in Table 1. A close inspection of this table illustrates how the history of lighting was radically altered by the new ways of harnessing energy that appeared around the time of the Industrial Revolution. For the mayor part of human history light came from the burning of wood, which is highly inefficient. A way of measuring

this using the amount of light in lumens (a measure of the total quantity of visible light emitted by a source) per certain amount of heat, sometimes measured in BTUs (British thermal unit, defined as the amount of heat required to raise the temperature of one pound of water by one degree Fahrenheit). An open fire would produce just 0.69 lumen-hours per 1,000 BTU, while a Babylonian lamp of sesame oil will produce 17.5, a tallow candle in the 1800s about 22.2, a whale oil lamp in 1815 circa 39.4, and a Kerosene lamp in the mid nineteenth century, 46.6. The first lamps produced by Edison in 1883 would produce 762 lumen-hours per 1,000 BTU, the Tungsten lamp will go from 1,088.6 in 1900 to 4,152 in 1990, and a compact fluorescent bulb in 1992 will produce 20,011 lumen-hours per 1,000 BTU [Nordhaus, 1996: 38]. That is, the same amount of energy was capable of producing much more (nearly 30,000 times more) light with the fluorescent light bulb than with the burning of wood.

Table 1. Main events in the history of lighting

1,420,000 B.C.	Fire used by *Australopithecus*
500,000 B.C.	Fire used in caves by Peking man
38,000-9000 B.C.	Stone fat-burning lamps with wicks used in southern Europe
3000 B.C.	Candlesticks recovered from Egypt and Crete
2000 B.C.	Babylonian market for lighting fuel (sesame oil)
Middle Ages	Tallow candles in wide use in western Europe
1798	William Murdock uses coal-gas illumination in Birmingham offices
1800s	Candle technology improved (use of stearic acid, spermaceti, & paraffin wax)
1820	Gas street lighting installed in Pall Mall, London
1855	Benjamin Silliman, Jr., experiments with “rock oil”
1860	Demonstration of electric-discharge lamp by the Royal Society of London
1860s	Development of kerosene lamps
1879	Swan and Edison invent carbon-filament incandescent lamp
1882	Pearl Street station (New York) opens with first electrical service
1920s	High-pressure mercury-vapor-discharge and sodium-discharge lamps
1930s	Development of mercury-vapor-filled fluorescent tube
1931	Development of sodium-vapor lamp
1980s	Marketing of compact fluorescent bulb
2000s	Spread of light-emitting diodes (LEDs) lamps

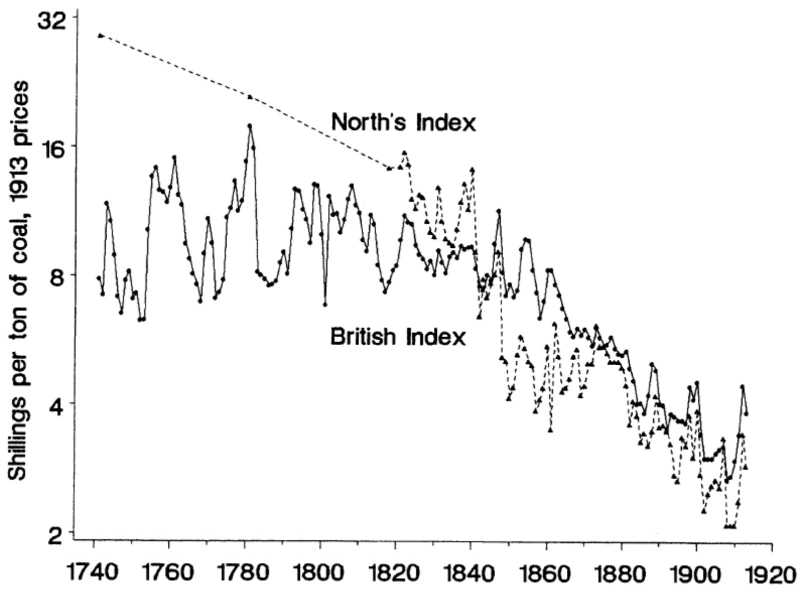
Source: Own elaboration based upon Nordhaus [1996: 32]

The way of harnessing energy that got the Industrial Revolution started was, of course, the steam machine. In 1712 Thomas Newcomen developed an ‘atmospheric’ steam engine that pumped water from a mine. Steam from the boiler filled a cylinder, water injected into the cylinder condensed the steam and depressed the piston, raising the pump. During the eighteenth-century water pumping remained the dominant use
of the machine. But a series of subsequent improvements made technology more flexible to be adapted to other uses, making the switch to steam the natural choice of the nineteenth century. The science writer Steven Johnson borrows the term ‘adjacent possible’ from scientist Stuart Kauffman to describe this kind of processes involving technology: many wonderful things can happen, but only *certain* things can happen. He writes that

> “*Good ideas* […] *are, inevitably, constrained by the parts and skills that surround them. We have a natural tendency to romanticize breakthrough innovations, imagining momentous ideas transcending their surroundings, a gifted mind somehow seeing over the detritus of old ideas and ossified tradition. But ideas are works of bricolage; they're built out of that detritus.*” [Johnson, 2010: 28]

Steam was everywhere. And because it was everywhere and could be adapted to many uses it became a major general-purpose technology. General-purpose technologies, like the water wheel or the heavy plough discussed earlier, have a series of characteristics that made them special [Lipsey *et al.*, 2005]: they typically start in a relatively crude form for very few purposes but increase in sophistication and efficiency as they diffuse (over decades, sometimes centuries) till they are used throughout most of the economy and for many different uses while having countless spill-overs in the form of externalities and technological complementarities. Lipsey *et al.* [2005] point out that the responses to a new general-purpose technology cannot be modelled as the consequence of changes in the prices of flows of factor services produced by the previous general-purpose technology, because most of the action is taking place in the technological structure of capital, so new possibilities depend on how one technology is related to another. That is, the most profound effects of steam came not from a fall in the price of power, but in making possible new products and processes that were technically impossible before. Because of this, it is the introduction of general-purpose technologies has the greatest chances of leading to a major disruption [Crafts, 2004].

Figure 9. Freight rate indices, 1741-1913 (deflated by UK GNP deflator, Ratio Scale)



Source: Harley [1988: 853]

Steam revolutionised many industries, but arguably its effect on transport had the greatest consequences for the economy at large. One of the reasons the Industrial Revolution had such a deep influence on society is because it contributed to reinforce Smithian growth, the main source of growth over the previous centuries, via the Transport Revolution of the nineteenth century. As discussed above, infrastructure investment in the form of channels and turnpikes contributed to expansion of markets in pre-industrial times, but putting steam machines into boats and locomotives took this expansion to another level [O'Rourke and Williamson, 1999: 33-34]. Steamships came first. The Marquis de Jouffroy d'Abbans in France came up with a design around 1776, while in Britain William Symington made the first practical steamboat circa 1801. The first commercial ships appeared in rivers in the early 1800s, and the first transatlantic trip in 1838. A series of additional innovations made these boats more efficient, such as the screw propeller or

steel hulls. But efficiency was also increased thanks to investment in large infrastructure projects, most notably the opening of the Suez Channel in November 1869, which almost halved the 12,300 miles' trip from London to Mumbai to 7,200 miles. Trains required new infrastructure to get started, so they took more time to take off. The first intercity service took place only in 1830, between Manchester and Liverpool. But since then rail mileage expanded rapidly in Britain to 6,600 miles in 1850, 15,500 in 1870, and 20,000 in 1890, and even faster in other places like the US (9,000, 52,900 and 116,700 miles respectively). Several innovations made both steamships and trains more efficient, or allowed to transport a greater variety of goods, such as the introduction of refrigeration (developed during the mid-nineteenth century). The impact on transport costs was substantial, as Figure 9 makes evident. Freight prices plummeted since the early 1800s, starting an era of ever-decreasing transport costs that will continue until today, and will foster Schumpeterian growth-stimulated Smithian growth on a global scale.

The infrastructure-technology link

The previous discussion raised a series of issues related to the role of technology and infrastructure as sources of growth but, at the same time, stressed the symbiotic relationship between them. Technology, infrastructure, and the services provided with the infrastructure are intimately linked in many ways. To begin with, technological improvement connected to infrastructure invariably leads to the creation of a new service:

> "*Nineteenth-century Europe saw a massive expansion of railway track, telegraph lines, electricity stations and cables, gas and water works and mains, followed at the turn of the century by tramways and telephone lines. Apart from water supply, these infrastructure industries were offering new services based on technological innovations*." [Milward, 2005: 6]

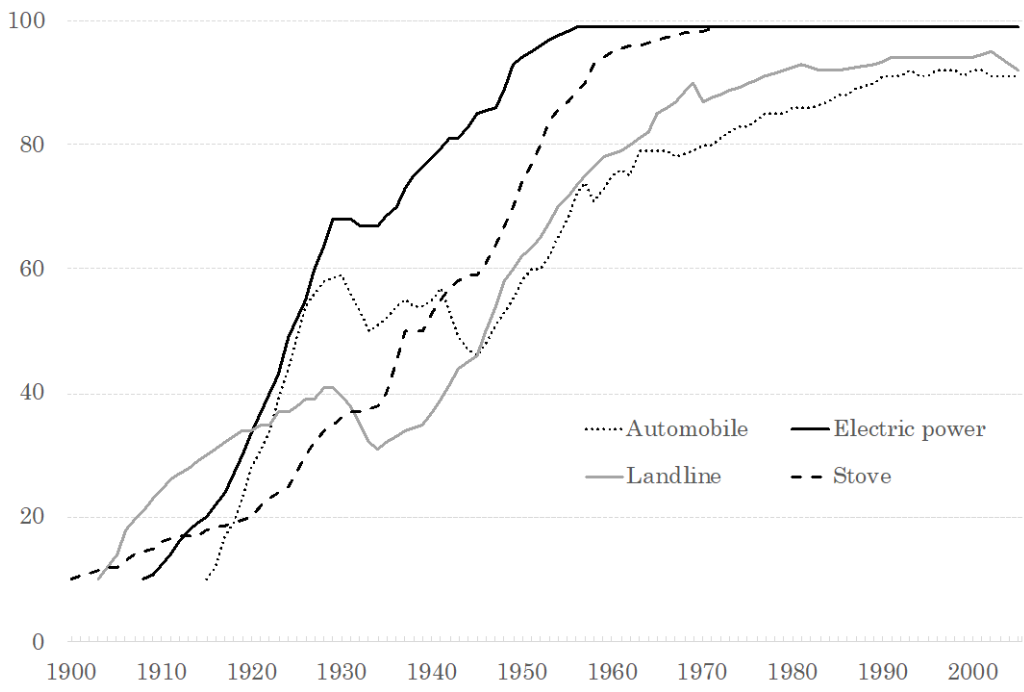
Although ex ante it is plausible to think that infrastructure leads to new services, the relationship between them is rather fluid, where services promote infrastructure and infrastructure, services. To provide an example, the telegraph (technology) did not need the communication grid (infrastructure) to be invented, but the latter was crucial to provide large-scale communication (service) [Standage, 1998]. Likewise, one does not need good roads or airports for the creation of cars or airplanes, yet their development can boost adoption by consumers. Quantity and quality of the infrastructure certainly affects technology adoption. Some of the recent debates on technology diffusion emphasise the idea that its speed is increasing, but it is far from obvious that this is inevitable or automatic, as domestic investment is normally necessary [Keller, 2004]. To profit from the new technology, it is necessary to get the infrastructure right, as illustrated by the fast adoption of electrical gadgets once the electrical grid was set up or the spread of cars once the roads networks were there:

> "*Transformation in the energy system derived from the progress of technical knowledge and associated innovations. These advances did not just occur in forms of energy generation or the invention of new processes (such as steam power or the internal combustion engine), but had to occur across a wide array of the supporting infrastructure required to put new technology into use*." [Kander *et al.*, 2013: 8]

Take Figure 10, which presents the evolution of technology adoption for some items in American households over the twentieth century. Patterns are overall similar, but some

gadgets required more infrastructure than others, which translated in different speeds of adoption. Stoves, for example, do not need an infrastructure, and its slow adoption was presumably largely determined by the alternative sources of heating available, or the actual need of heating. On the other side of the spectrum, electricity or telephone required a grid. Adoption of these innovations was then in good part determined by how much that grid had already developed and fast that it was further built. In the case of telephone landline, it was particularly slow: the telephone was invented in 1876, but seventy-five years later adoption was not reaching half of the households. Here the *characteristics* of the service are important. For telephones to work, a massive infrastructure has to be built, but the usefulness of the devices depends network effects (someone *else* has to have a phone) to make it appealing. Electricity is different. It does not face the same network effects (it is somewhat less relevant for my decision of adopting or not this technology whether another person is adopting it), and adoption appears to be faster. The case with automobiles is interesting because here part of the infrastructure *was* there (for horses and carriages), so early adoption was relatively easy, but then road improvements and automobile technology needed to co-evolve to make additional adoption worthwhile (not to mention the temporary break in the trend driven by the thirties crisis).

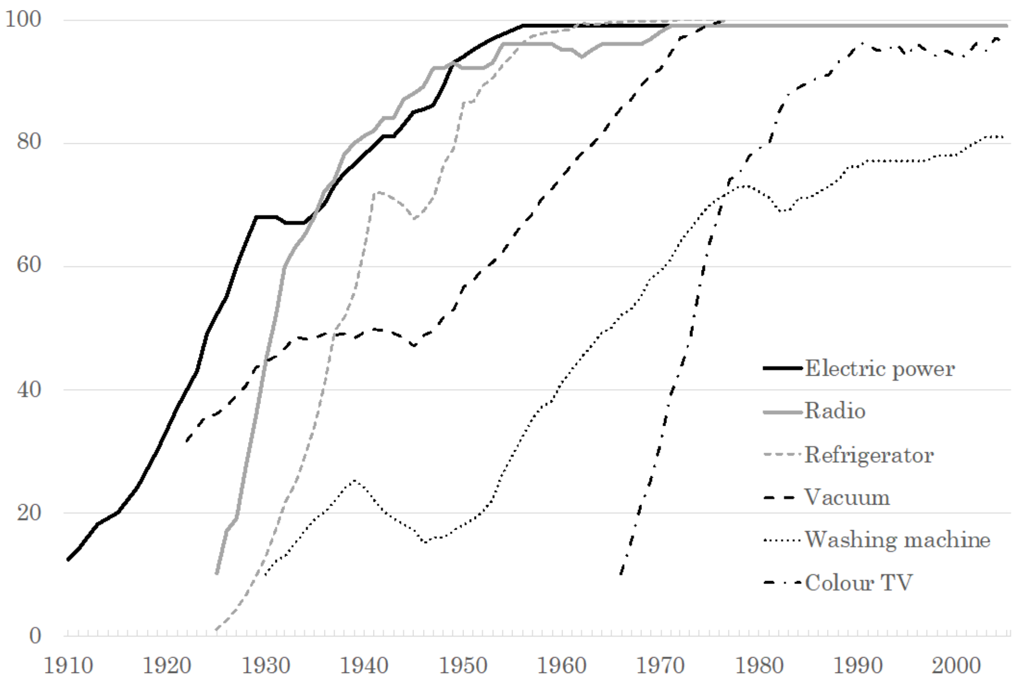
Figure 10. Technology adoption by households in the US, 1900-2005



Source: Own elaboration based upon information in https://www.visualcapitalist.com/rising-speed-technological-adoption/

Now, Figure 11 is identical to Figure 10, but compares adoption of electricity with adoption of gadgets that needed electricity to function. Clearly, the infrastructure favoured or placed a limit to the adoption of many innovations. Only radio surpasses electricity adoption, probably because some devices would run on batteries. The graph shows how relatively cheap goods (e.g. radio) or items with poor substitutes (e.g. refrigerator or TVs) are adopted rather fast, whereas 'luxury' goods such as vacuum cleaners of washing machines enter rather slowly in American households.

Figure 11. Technology adoption by households in the US, 1910-2005



Source: Own elaboration based upon information in https://www.visualcapitalist.com/rising-speed-technological-adoption/

The dynamics of interaction between infrastructure and technology do not need to be identical everywhere and, in fact, it seems they somewhat differed between 'leaders' (those pushing the technological frontier) and 'followers' (those picking up the cue and adopting technologies developed elsewhere). When the railway appeared in Britain, industrial development was well under way, but this was not the case in other relatively early industrialisers like Germany, and even less in the European periphery (e.g. Spain or Italy). Here the joined dynamics of Smithian and Schumpeterian growth are seen in full force, with growing markets increasing the possibilities of exchange, and latecomers able to catch-up to the leaders thanks to the high rates of growth stimulated by new technologies [see, e.g., Abramovitz, 1994]. It is then somewhat puzzling that adoption of new technologies is not universal. But the discussion before on the Spinning Jenny and other inventions during the Industrial Revolution already highlighted the fact that innovation does not imply adoption, and the point made by Allen [2009a, 2009b] was that relative prices are crucial to understand why. This logic extends almost naturally to ideas of human capital, which can be seen as another factor whose price is too high in certain regions where it is largely absent. But infrastructure can be another limiting factor, especially in places where the provision of public goods remains a challenge.

Also, the process of technology-infrastructure-service co-evolution is far from perfect, as technology creation and adoption are not driven by an entirely deterministic process. Along with cases of technologies never adopted because of lacking proper infrastructure development, there are cases of infrastructure becoming redundant because technology did not develop as initially expected. An interesting example of the latter is that of Milan's '*idroscalo*'. Very close to one of the current airports of that Italian city, the *idroscalo* is an artificial lake that was originally planned as a seaplane airport in the early twentieth century, in the heyday of that trend, and opened on 1930. It turned out that seaplanes for

passengers never really took off, and the lake became a recreational and sport facility. Will poor infrastructure in Latin American roads limit the adoption of autonomous vehicles, reducing the capabilities of the region to catch up with the developed world? Or will investment in that infrastructure turn out to be wasted resources, as in the case of the *idroscalo*, because people-carrying drones are here faster than we expected?

Private or public?

A last, yet not minor relevant point to have in mind when thinking about technological innovation in energy, transport, telecommunications, or water supply is that being part of a larger infrastructure sector, they tend to fall in a grey area between the public and the private sector. On the one hand, infrastructure industries contribute to satisfy a commercial demand, while at the same time provide a public service. On the other, many of the services associated with them tend to show some sort of externality which calls for the involvement of government to avoid the problem of under provision. As pointed out before, the problem of provision was slowly solved by societies in different ways. Over the long run there seems to have been a shift from private administration of infrastructure investment towards public organisation, and this seems to have followed a technology-driven dynamic [Milward, 2005]. Private enterprise and free trade were dominant before the nineteenth century at the national level. Recall the cases of channels or turnpikes in medieval times. Or windmills. The movement from private to public that took place later arguably had many sources. An important one is probably geopolitical and has to do with the consolidation of states in the nineteenth century. Some infrastructure was considered vital related to the strategic power fights between states. Many governments, for example, were very sensitive to communication channels, which had military potential [Milward, 2005: 290]. The consolidation of these new forms of government also called for efforts to build 'national character' through political and social unification. But another source of motivation to move from the private to the public sphere is technological. New technologies in the nineteenth century permitted –with the help of the suitable infrastructure– mass consumption of services that the previous technologies did not allow. There was a limit to the number of people to be transported by stagecoach, water brought by streams or the communication carried by messengers. Railways, water distribution networks and telegraph cables changed that. It made sense, given the high initial costs of infrastructure, to move from private to public, so the initial public involvement in infrastructure followed these innovations:

> "*In the 1830s and 1840s when the story begins, entrepreneurs in these sectors were seeking powers from local and central government for compulsory acquisition of land or of rights to use land. These tracks and distribution systems had all the characteristics of natural monopolies, and governments followed up the easing of rights of way by controlling prices and profits and by monitoring the engineering and financial soundness of the companies.*" [Milward, 2005: 289]

These same forces pushed towards full public involvement in many cases:

> "*…concern about natural monopoly, preserving national carriers, ensuring sovereignty over natural resources and airspace could be achieved by arm's-length concessions and regulation of prices and profits. The variety of strategic and political considerations associated with network spread and the expansion of services in railways, airlines and the telephone system could potentially have been secured by subsidies. By the end of the 1930s, the combination of regulation*

and subsidies was proving politically unpalatable. When this was added to the inability to support some services even with subsidy and with the desire in the case of telecommunications to control the flow of information, the balance was tipped towards state enterprise." [Milward, 2005: 294]

In the recent decades, it is government involvement, and its failure to provide competitive services that has become somewhat politically hard to accept. Even though in theory private provision of certain goods is not optimal, governments have failed to achieve minimum standards and the private sector have stepped in successfully. An interesting case of this relates to water supply. As it is well known, theoretically private water provision is expected to provide suboptimal levels of water (in terms of quantity and/or quality) because the difficulty to internalise health externalities. Yet there has been a series of cases where countries decided to pass on water supply to the private sector. Galiani *et al.* [2005] studied one such a case in Argentina during the 1990s and showed that the process of privatisation of the water sector triggered a decline of 8% in child mortality (26% in the poorest areas), suggesting the move away from the state had a strong positive effect on standards of living. And technological changes are permitting, even fostering a movement from centralised state provision to private supply, with many technologies allowing decentralisation, as might be the case with electricity storage and distribution, or the 'uberisation' of certain services.

3. IMPACT

Many of the dynamics described in the previous sections are of course mediated by the impact (actual or potential) these technologies have on the society. Needless to say, the way in which this shock materialises is rarely obvious, and never evenly distributed across different actors within that society, which creates important political economy implications for adoption, and eventual disruption of the new technology on the economy. One eloquent example of these dynamics comes from an unlikely candidate: a metal box. Few technologies have changed the shape of world economy in the last few decades as the container, extensively discussed in the unexpected best-seller *The Box* by Levinson [2006]. The Transport Revolution of the nineteenth century had shaken global trade in many dimensions, but what happened once ships reached the ports remained surprisingly similar to how things were done for centuries. Loading and unloading goods involved a lot of (quite dangerous) work, piling boxes, barrels, and bags on top of pallets, that had to be carefully placed (typically by human hands) in ships so that they will not move in high sea. In the early twentieth century it could take the same amount of time to load and unload five thousand tons of cargo than to cross the Atlantic from the US to Europe [Harford, 2017: 168]. In this context, the container made shipping incredibly cheap, and in doing so dramatically altered many parts of the economy:

"*The armies if ill-paid, ill-treated workers who once made their livings loading and unloading shups in every port are no more* […] *Cities that have been centers of maritime commerce for centuries* […] *saw their waterfronts decline with startling speed, unsuited to the container trade or simply unneeded, and the manufacturers that endured high costs and antiquated urban plants in order to be near their suppliers and their customers have long since moved away. Venerable ship lines with century-old pedigrees were crushed by the enormous cost of adapting to container shipping.*" [Levinson, 2006: 2]

But not all was bad:

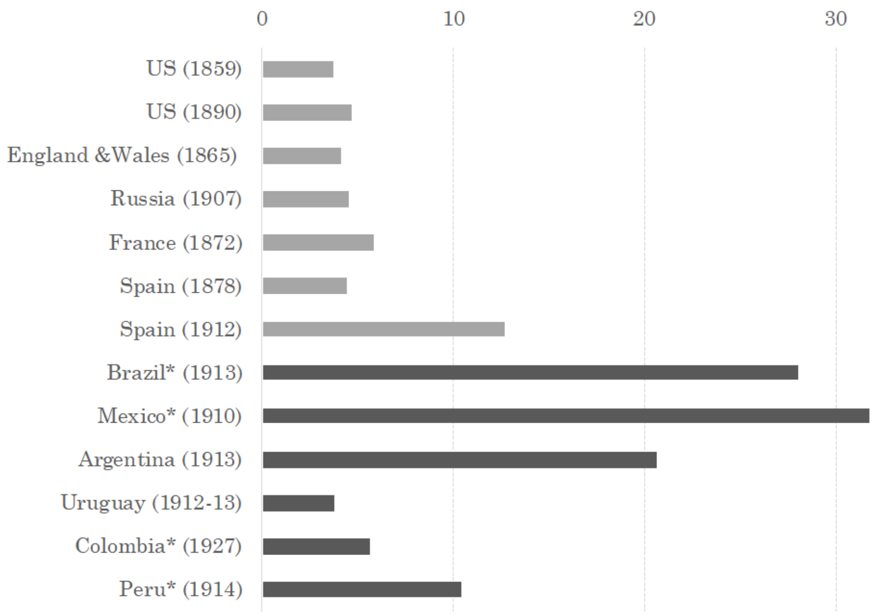
> "*Even as it helped to destroy the old economy, the container helped build a new one. Sleepy harbors* [...] *moved into the front ranks of the world's ports, and massive new ports were built* [...] *where none had been before. Small towns, distant from their great population centers, could take advantage of their cheap land and low wages* [...] *Poor countries, desperate to climb the rungs of the ladder of economic development, could realistically dream of becoming suppliers to the wealthy countries far away*." [Levinson, 2006: 2]

This was a huge achievement for a metal box, but certainly a mixed blessing for many. Increased variety of cheaper goods available raised living standards of consumers worldwide, but had an ambiguous impact on relatively immobile wage-earners, which partly explains why it took some time (and considerable negotiations) to get the container going (the other part was the difficulty of agreeing on the standard size of the container, again a problem intimately connected with finding the right infrastructure). New technologies bring both good and bad outcomes for societies, and almost in the end they invariably involve the ugly truth that failing to get into the wagon of those technologies normally leads the country to be left behind.

<u>The good</u>

Along with the container, there are many interesting cases one can explore of technologies that had a substantial, largely positive impact on society [see, e.g., Harford, 2017]. If we focus our attention on technological changes related to infrastructure, a natural place to explore is the transport revolution already partly discussed, which ranks among one of the most studied events in economic history [Bogart, 2013, 2019]. Here we know that innovation played a crucial role in the development of transportation (mainly the introduction of the steam machine), but it is also important to understand that, to realise these benefits, infrastructure was needed [Bogart, 2013]. The actual impact of this infrastructure is contentious. It was for example largely believed that railways were one of the main sources of growth in the American economy during the nineteenth century, but in a classic study using the concept of social savings (growth accounting exercise that evaluates implications of a new technology on economic growth), it was shown that they contributed only marginally [Fogel, 1964]. Interestingly, although this result was corroborated for other places in the developed world [e.g. Fishlow, 1965; O'Brien, 1983], for developing nations in Latin America the evidence to considerable social savings [Coastworth, 1979; Summerhill, 2005, Herranz-Loncán, 2014], suggesting the impact was larger in for 'followers'. This is shown in Figure 12 below.

<u>Figure 12</u>. Estimates of social savings of freight railway transport, several countries



<u>Sources</u>: Own elaboration from Herranz-Locán [2014: 15]. Western Europe and US in light grey, Latin America in dark grey. Asterisks indicates when the figure plotted is the average of available estimates: for Brazil, 18.0-38.0; for Mexico, 24.9-38.5, for Colombia, 3.4-7.9; for Peru, 3.7-6.7.

In many cases, large savings were obtained not from improvement in market expansion through lower freight rates, but on integration of labour markets, thanks to decreases in commuting times for passengers. Tim Leunig studied this for England [Leunig, 2006]. He showed that there were fare savings with the introduction of the train, but time savings dominated creating a new good: travel for the masses. Accounting for the savings in time, railways probably contributed to a sixth of the economy-wide growth between the mid-nineteenth and the early twentieth centuries. This example illustrates the difficulty, already hinted by Nordhaus' study on lighting [Nordhaus, 1996] or a related one he carried out on computers [Nordhaus, 2007], of accurately measuring the impact of a new technology, because the simultaneously change costs, the way we consume things and the kind of things we consume. This problem is magnified with the introduction of general-purpose technologies like the steam engine or information technology, as they advance rapidly, are adopted by a wide range of sectors and households, and spur inventions and innovations in other sectors [Lo and Sutthiphisal, 2010].

<u>The bad</u>

If new technologies hold the potential for doing so much good, why is it that they still tend to generate so much anxiety in the public? Mokyr *et al.* [2015] have organised the various reasons for this into different types, and two of them are of interest for the discussion here. In the first, we have anxieties related to the moral implications of innovation. The Prometheus myth is one of the earliest recorded incarnations of this. One of the most recent (in historic times) was Mary Shelley's *Frankenstein* (aptly subtitled *The Modern Prometheus*), whose main idea is summarised in a sentence of the novel: "*Nothing is so painful to the human mind as a great and sudden change*." Why this is so, it is hard to say. Part could well be cultural persistence. The same thing that have contributed to our

success as a specie, the fact that we are cultural animals, could be stopping us from generally welcoming change [Henrich, 2015]. It is also true that new technologies involve to a greater or lesser extent uncertainties, and some of these uncertainties might be harmful. Any risk-averse rational agent will hesitate to adopt a change given that information problem. Tobacco smoking was thought to be a healthy habit for a long time, CFCs were considered revolutionary when they were invented in the 1920s, nobody believed asbestos were dangerous for a long time after their introduction in the late 1860s [Mokyr, 1994]. But just as there are things were thought to be good that turned out to be disastrous or disappointing, there are other that were thought to be terrible that turned out to be positive or useful in the long term. Entire societies rejected innovations that are now ubiquitous. There are innumerable examples of this in history. When they first appeared, cars caused certain amount of terror. In the summer of 1907, for example, an American newspaper reported that:

> "*Though the newspapers chronicle accidents and fatalities resulting from the automobile craze, they do not begin to touch the real terrorism of this fad… Carriages are smashed, children are run down without a look back to inquire of the consequences and the pedestrian at every cross-street in town… is in constant terror for his life*" [Pittsburgh Gazette, August 21, 1907]

But a generation before, in 1881, a note in the New York Times pointed out that one reader considered "*the bicycle to be the most dangerous thing to life and property ever invented. The gentlest of horses are afraid of it.*" Medical doctors were notoriously reticent to use soap between interventions up to the late nineteenth century, unable to believe *they* were causing death in hospitals [Gawande, 2007]. We are still arguing if genetically modified food is friend or foe. And, following the infamous fraudulent 1998 paper by Andrew Wakefield connecting vaccines with autism, we are strangely back to debating whether vaccination is good or not. This stirred up society more than two centuries ago, when Edward Jenner introduced inoculation of smallpox using cowpox in 1798, as illustrated by the cartoon reproduced here in Figure 13. For whatever reason, these and other inventions were considered themselves wrong, or to lead to morally inacceptable behaviour on the part of individuals that used them.

A slightly different way in which innovations were ethically wrong was that they were typically associated to a privilege for the rich. Right now, solar panels or electric car clearly fall in that category, but TV sets and refrigerators also belonged to that category not long ago. Mobiles phones, that are now ubiquitous in the poorest countries in the world, were restricted to an elite in the 1990s. And the same happened with telephone lines decades ago. When the first telephonic conversation between Europe and America appeared, the Gettysburg Times reported that the "*wireless telephone will be too expensive to become a public service, but it will be a boom to privileged persons*" [Gettysburg Times, July 10, 1914]. In numerous cases people fail to see that many innovations, if successful and eventually improved, tend to reach many sectors of society, moving down the social ladder.

Figure 13. 1802's cartoon on the effects of inoculation

Notes: "The Cow-Pock—or—the Wonderful Effects of the New Inoculation!" was produced by caricaturist James Gillray in 1802, a few years after Edward Jenner administered the first vaccine, to illustrate the fear patients had of being vaccinated via cowpox (notice how many are growing cow-like appendages).

The second group of anxieties relates to how the introduction of innovations affects the technological *status quo*. That is, whether the new technology will substitute machines for labour, as suggested by the Luddites in the early nineteenth century. As vividly described by Schumpeter [1942], technology is the driving force behind creative destruction. The old is replaced by the new. It is quite telling that one of Schumpeter's most famous examples of the way the economy evolves in this sense is, actually, related to technological change in transportation and infrastructure: railroads, and specifically the Illinois Central Railroad, replacing mail coach [Andersen, 2002]. The 'railroadisation' of the American Midwest upset "*all conditions of location, all cost calculations, all production functions within its radius of influence and hardly any 'ways of doing things' which have been optimal before remain so afterwards*" [Schumpeter, 1939: 102]. As railroads expanded, so did many activities around them: the actual manufacture of trains, products that could be transported on the railways, and of the infrastructure around the railroads themselves. This was also accompanied by regional development. But also, many types of farming and agricultural systems in the Midwest were destroyed. As new and more efficient means of transportation were created, an entire way of life was destroyed. The most direct victim was mail coach. Farmers also moved from subsistence farming, growing crops that they needed, to more commercial farming, growing crops for the market that could be transported by rail. Which kind of job is actually destroyed in this sort of processes is not entirely clear, and arguably it has changed over time. Acemoglu [2002], for example, argued that the nature of this process changed radically from the nineteenth to the twentieth

century. During the first and second Industrial Revolution the process was mainly deskilling, where machines replaced skilled labour. Technological change favouring skilled labourers is really a phenomenon of the twentieth century.

But many of the discussions on the extent of machine substitution for human labour, specially by the media, typically ignore the "*strong complementarities between automation and labour that increase productivity, raise earnings, and augment demand for labour*" [Autor, 2015]. There is a limit to this substitution, what Autor talks about the Polanyi's Paradox, after the economist and philosopher that stated that "we know more than we can tell". Autor explained that:

> "*…there are many tasks that people understand tacitly and accomplish effortlessly but for which neither computer programmers nor anyone else can enunciate the explicit "rules" or procedures. […] When we break an egg over the edge of a mixing bowl, identify a distinct species of birds based on a fleeting glimpse, write a persuasive paragraph, or develop a hypothesis to explain a poorly understood phenomenon, we are engaging in tasks that we only tacitly understand how to perform. […] the tasks that have proved most vexing to automate are those demanding flexibility, judgment, and common sense—skills that we understand only tacitly*" [Autor, 2015: 11]

Figure 14. Mean probability of automation by occupation

Sources: Own elaboration from data in Nedelkoska and Quintini [2018: 51].

In the last few years there has been some estimations on the risk of losing the job due to computerisation or automation [e.g., Nedelkoska and Quintini, 2018], and Figure 14

collects some examples of this. Occupations mainly consisting of tasks following well-defined procedures than can easily be performed by algorithms are at higher risks than others. Many types of clerks, bookkeepers and accountants, for example, are at a particular high risk (a probability close to 1 if being computerisable), while activities that involve more sophisticated tasks like the work carried out by physicians, surgeons or elementary school teachers are very unlikely to be computerised in the short term [Frey and Osborne, 2017].

The presence of these anxieties contribute to what is perhaps one of the greatest challenges regarding technological change, its political economy [see, e.g., Mokyr, 1992, 1995]. People will stop change, because they fear it, they feel they are unfair, or because it affects their individual benefit, regardless of the potential benefits for the society as a whole. If those who want to stop creation or adoption of new technology have any sort of political power, either *de jure* or *de facto* [Acemoglu *et al.*, 2005], they will be very likely to succeed. This is, alas, unavoidable. But societies can, through their institutions, set up a system that ameliorates these dynamics, protecting those creating or adopting new technologies, establishing ways of compensating the losers, or other mechanisms, as England in part did during the Industrial Revolution.

Yet another potential problem with new technology is related to the issue of uncertainty mentioned before. The new markets innovations generate are typically hard to understand, and they might generate 'irrational', or apparently irrational behaviours in the society. Kindleberger and Aliber, for example, noticed the correlation between super-skyscrapers and asset price bubbles:

> "*Consider some of the tallest office buildings in the world. The Empire State Building in New York City was started in 1929. The Petronas Twin Towers in Kuala Lumpur were started in 1993. The Jailing Tower in the Pudong area of Shanghai was started in 1995. In the late 1980s it seemed like half of the building cranes used to construct tall structures were in Tokyo. By the mid-1990s many of these cranes had migrated to Shanghai and Beijing.*" [Kindleberger and Aliber, 2005: 97]

The connection between 'bubbles' and economic euphoria have been documented in many places. While some, like Kindleberger and Aliber [2005] or Shiller [2000], suggest good part of this is due to irrational behaviour, authors like Garber [2000] still champion the idea that economic fundamentals provide a good explanation of most bubbles. Novelty of large markets seem to be one of these recurrent explanations. When talking about the Mississippi and South Sea Bubbles, for example, Garber [1990] points out that they were "*vast macroeconomic and financial experiment…[t]rue, the experiment failed, either because its theoretical basis was fundamentally flawed or because its managers lacked the complex financial skills required to undertake the day-to-day tactics necessary for its consummation*" [Garber, 1990: 53]. Large infrastructure projects are also prone to this problem. When Shleifer summarises some of the major bubbles in history, along with the Tulipmania and the ones mentioned above, he includes many of the railway construction: the British first railway boom (1845-6), the American 1873 railway boom and crash, or the 1920s Florida land boom (linked to the building of railroads and development of Miami) [Shleifer, 2000: Table 6.2]. This kind of behaviour was modelled by Pástor and Veronesi [2009], that show the connection between technological revolutions and the evolution of stock prices.

The ugly

Still, technological change is one of the most important determinants of income growth, and the ugly truth is that for most people in the developing world the failure to jump-into-the-wagon means lagging behind in development. This is, unfortunately, a fairly common problem, which comes somewhat as a surprise as useful knowledge is hard to be kept as a secret. But, as I have already discussed, it might be that the new technology simply does not pay, as it did not pay to use the spinning Jenny in France in the nineteenth century, because factor prices in the poor economy still favours the low capital alternative. The political economy problem I highlighted in the previous section is also a limitation. But other factors might be at play. Knowledge might be prone to leaks, but sometimes it also requires additional, complementary knowledge to work, generating what economics call 'increasing returns' in knowledge. The presence of these types of returns make the dynamics of knowledge accumulation to follow certain virtuous or vicious circles [Easterly, 2001: 153] that could leave countries in poverty traps. And infrastructure faces the same problem of increasing returns, which opens the door for government intervention.

4. DISCUSSION

It is of course hard to say how much technological disruptions are going to affect societies, but the study of the past provides a series of hints. These sorts of disruptions are –for once– not new, and there are no reasons now is different. In pre-industrial times 'disruptive' technologies like the heavy plough, or new kinds of sails, took considerable time to gain momentum. Since the industrial revolution, however, the pace of change has increased considerably, and technological disruptions of some sort have become relatively common. Perhaps the things that are likely to cause large distortions are the introduction of general-purpose technologies that can easily spread between sectors. It is hard to say if any such technology is really among the ones now claimed as 'imminent', but the new ways of storing energy are a likely candidate.

Anxiety about it is not new either, still seems hard to avoid. Impact on society is typically positive in the long term, but there are short run distortions along with long run benefits. If new, welfare improving technologies materialise, several factors could impede their adoption, leading to a lagging behind of 'follower' economies. Part of the society will be negatively affected; if they have the power to influence adoption, they will. In this context, underdeveloped infrastructure could be a major limitation for poor countries to grow. Regulation could also play a major role to make transition smooth

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