THE UNIQUENESS OF WESTERN INNOVATION, 1700-1850

Leonard Dudley, Sciences économiques, Université de Montréal

leonard.dudley@umontreal.ca

March 13, 2013

Abstract

Between 1700 and 1850, people in several urban regions of Western Europe and North America learned to innovate at a rate that was unprecedented in world history. The explanations of the Industrial Revolution offered recently by Mokyr (2009) and Allen (2009) – namely, national differences in institutions, ideology and factor prices – fail to explain the differences between innovating and non-innovating regions *within* states. This paper first explores how the structure of social networks affects people's ability to innovate. The study then tests this social-networking approach. With a sample of 201 urban regions and 117 innovations from the period 1700-1850, it is shown that the institutions and market conditions have less explanatory power than three variables which capture the roles of agents in social networks. The latter influences were missing in eighteenth-century China.

Paper to be presented at the Appalachian Spring: Eighth Annual Conference in World History and Economics, Appalachian State University (Boone, NC), April 20, 2013.

I. Introduction

> On proceeding up to Whampoa [a way station on the Pearl river between Macau and Canton], three more dismantled forts were observed, and at 4 p.m. the *Nemesis* came into that anchorage having … destroyed five forts, one battery, two military stations, and nine war junks, in which were one hundred and fifteen guns and eight ginjalls [large swivel-muskets], thus proving to the Chinese that the British flag can be displayed throughout their inner waters.
>
> -- Report of Commodore J. J. G. Bremmer to the Earl of Auckland, 1841[1]

The *Nemesis* was a 184-foot (56 m) steam-powered paddle frigate purchased by the East India Company in 1840, during the First Opium War. With an iron hull and a draft of only five feet, it could sail inland up rivers that ocean-going wooden ships could not navigate. It was also the first warship to have watertight bulkheads. Armed with two precision-built 32-pound cannon, several smaller guns and Congreve rockets, the *Nemesis* was so deadly that the Chinese referred to her as the "devil ship" (Headrick 1981, 47-50). Yet ironically, it was the Chinese who had first developed cast iron, firearms, paddle-wheel boats and ships with multiple watertight compartments (Mokyr, 1990, 210, 215, 221; Needham 1965, 417).

During the late Middle Ages and the Early Modern period, Europeans had developed few new technologies themselves, although they had been able to improve Asian inventions such as paper, the compass and printing with movable type (Mokyr 1990, 215-218). Then between 1700 and 1850, the people of several regions of Western Europe and North America began to innovate at a rate that was unprecedented in world history. As the example of the *Nemesis* indicates, the discoveries of this period, such as the smelting of iron with coke, the steam engine and machine tools, would allow the West to dominate the rest of the world militarily and economically.

Historians have long debated the causes of an apparent decline in Chinese innovation after the fourteenth century.[2] It is now clear that the Chinese did not altogether stop

---

[1] Headrick (1981, 50).

inventing; for example, the bristle toothbrush, bronze movable type and petroleum lamps all appeared under the Ming Dynasty (1368-1644).[3] The more important question in discussing the Great Divergence is: what changed in the modern period to allow the *West* to innovate at a rate that was without precedent?

Recently Joel Mokyr (2009) and Robert Allen (2009) have explained Britain's lead in the Industrial Revolution by national differences in ideology and factor prices. In *The Enlightened Economy*, Mokyr (2009, 30-37, 66-67) used a *supply-side* approach to explain Britain's lead in industrial development between 1700 and 1850. Like Douglass North (1981, 1990), he pointed to the impact of institutions, defined broadly to include not only Britain's parliament, courts and its formal and informal educational system, but also the practical science of voluntary groups such as London's Royal Society and Birmingham's Lunar Society. As North and Barry Weingast had earlier noted, the Glorious Revolution of 1688 had led to a series of reforms that favored the rule of law and the respect of contract and property rights (North and Weingast 1989).[4] Moreover, throughout the eighteenth century, Mokyr argued, the British Enlightenment with its emphasis on "useful knowledge" encouraged the application of mathematics and science to satisfy social needs (Mokyr 2002, 63-65).[5]

These authors were not mistaken in arguing that by 1700 British institutions and culture were favorable to industrial improvement. What is not so clear is that these features were sufficiently different from similar tendencies elsewhere in Northern Europe to explain the difference in rates of innovation observed over the period from 1700 to 1850. Perhaps the most reliable statistics on the protection of individual rights are rates of homicide, since killing people is a crime in virtually all societies and the evidence is relatively complete and free of error. Manuel Eisner has compared the declines in

[2] For a recent review of the "Great Divergence" question, see Duchesne (2011, 170-181), whose title I have borrowed in part for this paper. Eric Jones (1981) also drew attention to the divergence question in the "European Miracle".

[3] Bowman (2000, 601), Temple (1986, 80).

[4] In a recent book, Daron Acemoglu and James Robinson (2012) have extended this institutional argument to explain why some societies became rich while others long remained undeveloped.

[5] For Gregory Clark, there was a genetic component to British willingness to work and to save. Prior to the Industrial Revolution, the wealthiest in England had twice as many surviving children as the poorest. As a result, the genes of the former were spread by selection through the population (Clark, 2007 pp. 6-8).

homicide rates in England, Belgium and the Netherlands, Scandinavia, Germany and Switzerland, and Italy from the Middle Ages to the present. By the eighteenth century, homicide rates in England and Scandinavia were virtually identical. Although the Low Countries had a somewhat higher homicide rate than these regions in the eighteenth century, by 1800, they too had very low levels of violence (Eisner 2003, 99). We see, then, that if homicide rates are an indicator of the rule of law, there was nothing remarkably different in the institutions and culture of England to distinguish it from the rest of Northern Europe.

In a second study, Allen (2009) presented an alternative, *demand-side* approach to innovation, focusing on market forces. He emphasized the role of factor prices in triggering trajectories of technical progress in several key sectors of the British economy. High real wage rates and cheap coal, he argued, provided an incentive to devise production processes that substituted cheap capital and coal-based energy for expensive labor and wood-based energy. Subsequently, in each sector, as a result of learning from experience, there followed a series of adaptations that improved the productivity of the initial processes. These later steps were relatively insensitive to factor prices (Allen 2009, 151-155). Another crucial question in the development of the initial inventions that set off these innovation trajectories was the size of the market for new techniques.

Once again, the evidence presented is not sufficient to explain either the location or the timing of the key innovations. The argument fits for the Midlands and Lancashire. However, before 1775, real wage rates were even higher in Amsterdam than in London (Allen 2009, 40). And coal from Newcastle was no cheaper in southern England than in the Netherlands (Vries and van der Woude 1997, 719). Yet London accounted for a fifth of the world's important innovations between 1700 and 1850, while no Dutch city had a single important innovation during this period.[6] Moreover, the northeast, Scotland and Wales which had rich coalfields accounted for few innovations (Dudley 2012, 127). As for the timing, Nicholas Crafts has pointed out that Allen's own data would support development of the jenny in England a century before James Hargreaves invented it (Crafts 2010, 158-159).

[6] See Table 1 below.

By focusing on national characteristics, both Mokyr and Allen failed to take account of the differences between innovating and non-innovating *regions* within the industrializing states. The next section will describe examine the geographic concentration of innovation, not only across countries, but also between regions within individual states. Section III then suggests an explanation for this concentration by examining how the structure of *local* social networks affects people's ability to come up with new ideas, that is, to innovate. We will meet three types of people who, according to author Malcolm Gladwell, are indispensable if such a network is to function effectively (Gladwell 2000). By the middle of the nineteenth century, thanks to these innovators and their fellows, British industry had become a "network of mutuality".[7] Similar innovation networks had also developed in northern France and the north-eastern United States – but not elsewhere on the planet.

We test this social-networking approach to innovation against competing hypotheses that focus on institutions, ideologies and factor prices. Section IV will present the methodology and describe the data – a sample of 201 urban regions and 117 innovations from the period 1700-1850. Section V will present the results. It is shown that national characteristics and market conditions have less explanatory power than three variables which capture the roles of agents in social networks. These additional considerations are: (1) open and flexible local institutions, (2) literacy in a language with a phonetic script and (3) the standardization of the vernacular language across regions. Finally, Section VI will compare the West with China in order to understand why rapid innovation was unique to the North Atlantic community during the period under study.

[7] This expression is from Martin Luther King Jr., *Letter from Birmingham Jail*, 1964.

II. Space, Time and Cooperation

In most previous studies of the Industrial Revolution, the focus has been on *national* differences in rates of technological progress. The usual procedure has been to contrast the innovative success of Britain with the technological stagnation of the continent, at least prior to the second quarter of the nineteenth century. This approach is justified provided that we may assume that innovation occurs relatively evenly across regions and over time *within* each state. In this section, we will examine the validity of this assumption by examining the distribution of 117 important innovations across 201 urban regions of the West over the three half-centuries from 1700 to 1850.

In addition to their distributions through space and over time, there is another feature that distinguishes the inventions of the Industrial Revolution – one that has been overlooked in most previous studies; namely, the degrees of cooperation. As we will see in the next section, cooperation between inventors may have been essential to generate many of the key breakthroughs. Accordingly an innovation was defined as cooperative if two or more unrelated people made significant contributions to its initial conception and subsequent development.

How was the set of innovations chosen? To avoid bias in favor of discoveries made in particular countries, this study chose recent accounts of innovation by recognized experts of four different nationalities. These were studies by Donald Cardwell (1991) of Britain, Maurice Daumas (1979) of France, Joel Mokyr (1990) born in the Netherlands and living in the United States, and Akos Paulinyi (1989), born in Hungary and residing in Germany. To be considered an innovation here, a technological development had to be mentioned by at least two of these authors. Although the overlap between the four was considerable, the *Encyclopedia Britannica* served as arbitrator in the cases of a reference by a single author. In Table 1, the resulting innovations are presented for 1700-1749, 1750-1799 and 1800-1849, respectively. Cooperative innovations are shown in bold face.

INSERT TABLE 1 ABOUT HERE.

Combining the data on innovation and estimates of population, we obtain in Figure 1 the number of innovations per million inhabitants. This measure indicates that innovative effort was concentrated in three states. As the lower set of histograms shows, in total innovations Britain out-performed all other societies in each period, with more than one important innovation per million inhabitants. However, after 1750, there was increasing competition from France and the beginnings of rivalry with the United States. The figure shows clearly that the Industrial Revolution was not a purely British phenomenon. Rather, it was a general process whose pattern appeared first in Britain and France but subsequently spread to the United States. For a century and a half, these three countries – the only societies able to develop cooperative innovations – dominated the innovation process in the West.

INSERT FIGURE 1 ABOUT HERE.

Figure 2 presents this same information by urban region, with non-cooperative innovations on the horizontal axis and cooperative innovations on the vertical axis. A 45-degree line helps to indicate the intensity of cooperation in each city. We see that the innovation process was also highly concentrated at the regional level within the three leading countries. In the upper graph, corresponding to the first half of the eighteenth century, we see that innovation began in Great Britain and France, where Birmingham, London and Lyon took the lead. Birmingham also distinguished itself by the observed willingness of its inventors to cooperate with one another, accounting for three of the four cooperative innovations in this period. Four other cities (Manchester, Oxford, Edinburgh and Dresden) each had a single non-cooperative innovation.

INSERT FIGURE 2 ABOUT HERE.

The middle graph of Figure 2 presents the innovations of the following half-century, 1750-1799. Birmingham and London continued to stand out, but they were joined by Paris. Together, these three centers accounted for 33 of the 53 innovations of this period, including 19 of the 23 classified as cooperative. In Britain, Manchester, Plymouth, York and Glasgow were other urban regions that had multiple innovations, along with Philadelphia in America. Eight other centers, including Basel, Bern, and Munich, had a single, non-cooperative innovation. From the initial sparks in Britain France, and Britain's American offshoot, the flames of innovation would appear to have spread – both within the initial centers (Lyon excluded) and in a few neighboring cities of these countries. The rest of the West, including large regions of Britain and France remained largely untouched by the innovation process.

By the first half of the nineteenth century, Britain, France and the United States would appear to have reached a tipping point at which innovation had become self-sustaining. Remarkably, however, Birmingham and Paris, two of the principal center of new technologies in the eighteenth century appear to have exhausted much of their initial stocks of ideas. Paris dropped to two innovations and Birmingham to a single new technology (within the group of seven on the vertical axis). In Britain, Manchester replaced its Midlands neighbor in total number of innovations, but with a much lower intensity of cooperative innovation. In France, seven cities outside Paris (including Lyon) had a single innovation.

When we attempt to understand the extreme geographic concentration of innovation between 1700 and 1850 shown in Figure 2, three features stand out. A first characteristic is the almost complete absence of southern Europe – France below the Loire valley, Austria and Italy. Only Como and Montpellier managed each to contribute a single important novelty. A second surprise is the nonappearance of numerous wealthy regions of northern Europe – the present-day Netherlands, Belgium and (with three exceptions) Germany and Scandinavia. At the beginning of the period, the Netherlands was by far the most prosperous state in terms of per-capita income, while Belgium, Denmark and Sweden all had higher per-capita GDP than France (Maddison 2007, 382).

A third feature in Figure 2 is the remarkable performance of Birmingham and Manchester, two centers that in 1700 were small towns with populations of under 10,000 (Bairoch, Batou and Chèvre 1988). Together, they were responsible for almost 30 percent of the important innovations over the next century and a half. It might be argued that since these towns were in close proximity to the coal fields of the Midlands and Lancaster respectively, they were in a privileged position for the development of steam-powered machinery. However, since these centers were with Bradford the only cities in our sample not dominated by municipal corporations, their success may be due in part to other considerations. In France, Lyon, with four innovations over this period, proved considerably more inventive than cities of comparable size, such as Marseille, Lille, Bordeaux, Toulouse and Nantes, all of which had none.

In this section, we have seen first that innovation during the Industrial Revolution was geographically highly concentrated by country: three present-day states accounted for 95 percent of all innovation. Second, *cooperative* innovation was even more highly concentrated: these same three states produced *all* of the cooperative innovations. Finally, within these leading countries, innovation was also highly concentrated. A half dozen urban regions – London, Birmingham, Manchester, Paris, Lyon and New York – accounted for 70 percent of all the innovations and 78 percent of the cooperative innovations. These facts are hard to explain by the institutions of a single state or by the distribution of coal reserves. Might they, however, be the consequences of a restructuring of communication networks? We turn to this question in the next section.

III. Innovation and Social Networks

Where do new ideas come from? One is tempted to shrug and say that they are most likely random events, like mutations of DNA. However, in his section, we will see that accelerated technological innovation may be explained better by systematic changes in social networks.

In his book, *The Act of Creation*, Arthur Koestler, a Hungarian journalist and novelist proposed an answer to this question based on the invention of the printing press. Its inventor, Johannes Gutenberg, was familiar with the coin-maker's punch that could produce multiple copies of a letter or symbol. But how could he apply a number of such individual punches evenly so as to leave a clear impression of a block of text on a sheet of paper? One day, while taking part in the wine harvest near his Rhineland city of Mainz, Gutenberg suddenly realized that the wine press could be adapted to apply uniform pressure to a page of metallic type so that it would leave a readable impression on paper (Koestler 1964, 121-123). Here, then was a possible model of innovation: two frames of thought are brought together, often by accident, in the mind of a single person. In this section we shall see how during three fifty-year periods after 1700, the development of social networks was closely linked to innovative success. First, however, consider a recent extension of Koestler's intuition.

Gilles Fauconnier and Mark Turner extended Koestler's ideas in their 2002 book, *The Way We Think*. The two linguists suggested that by a process of *conceptual blending*, one subconsciously integrates elements from various frames of reference to form something new. As the most complex form of such integration, they proposed the concept of a *double-scope network*, which takes as inputs two different organizing frames and then combines them to form a blend that has "emergent structure of its own" (Fauconnier and Turner 2002, 131). Koestler's example of Gutenberg's invention of the printing press, by integrating the coin-maker's punch and the wine press into a completely new structure, is a good example of this process.

Fauconnier and Turner argued that both language and complex innovation may be the result of a quite recent evolutionary development. Perhaps 50,000 to 70,000 years ago, the gradual evolution of the integrating capacity of the human brain reached a critical point at which double-scope blending became possible (Fauconnier and Turner 2008, 180-183). Suddenly there emerged language, with its extraordinary capacity to compress thousands of bits of information into a few words. According to Fauconnier and Turner, the same neurological developments that permitted language also made possible scientific discovery, design, mathematical thinking and, eventually, computer interfaces (Fauconnier and Turner 2008). These new mental capabilities allowed by double-scope blending in turn reinforced one another (Fauconnier and Turner 2002, 186).

However, if innovation does require double-scope integration in this way, does it necessarily follow that cooperation between two or more individuals is necessary? Since the 1990s, evidence has been accumulating to show that there are cognitive bottlenecks when we try to do two complex tasks at the same time; for example, driving and talking on the phone (Pashler, 1994). In particular, our ability to choose from among two or more actions and to recall from memory would seem to be limited. When two different tasks require the same operations, conflict between them slows the response time. Moreover, recent research suggests that there are limits to our ability to learn *how* to multitask. People who change tasks frequently are, surprisingly, able to switch tasks less easily than those who multitask less often. Research by Eyal Ophir and his colleagues at Stanford University suggests that the heavier the use of multiple media, the more prone a person is to interruption from irrelevant thoughts retrieved from memory (Ophir, et al., 2009). If innovation requires the merging of multiple frames of reference in very different areas of activity, it may be efficient, then, for a researcher to download some of these areas of reference to a collaborator, rather than to attempt to do everything herself – that is, provided the potential partner may be trusted.

The Tipping Point

But how does a society change from a state in which everyone regards strangers with suspicion to a situation in which people are willing to cooperate with one another?

Malcolm Gladwell has suggested that three types of individuals are critical in enabling a new form of behavior, such as trusting strangers, to spread within a society. Generally, little happens for a certain time until unexpectedly the balance tips, as many people suddenly change their ways of thinking and behaving. One of the key roles in this process is the *maven,* a person who accumulates information and willingly shares it with others – a term derived from a Yiddish word meaning "one who understands" (Gladwell 2000, 60). In addition, a second type of individual is required to bridge the gap between people who do not usually interact with one another. Malcolm Gladwell has described such people as *connectors* – individuals with a talent for bringing people together to share their common interests (Gladwell 2000, 38). Yet a third type of individual is the salesman, whose role it is, through persuasion, to change the opinions of people who are initially unconvinced by a particular message (Gladwell 2000, 70).

Network Theory

Let us consider how these three roles help explain the formation of innovation networks in Britain during the early 1700s. The upper graph in Figure 3 shows the formation of an embryonic network such as the one that took shape in the West Midlands during the first half of the eighteenth century. Points D and T represent maven Abraham Darby and his apprentice John Thomas who set up an iron works fueled by coke at Coalbrookdale in 1709 and sought markets for their castings (Percy, 1864, p. 887). Point A is a mine owner who may have had dealings with Darby. New to the region in 1712 came another maven, Thomas Newcomen, with his partner John Calley, N and C respectively, eager to disseminate a new technology that used steam to replace natural sources of power. They convinced mine owner A to use their atmospheric steam engine to replace horse-powered pumps. Then, in 1722, Darby's firm started a relationship with Newcomen and Calley, who were looking for a reliable supplier of iron castings (Rolt 1965/1986, 56) . The resulting links closed the circle to form a ring network.

INSERT FIGURE 3 ABOUT HERE.

As Sanjeev Goyal has explained, there are several possible measures of interest when one studies a network. One such dimension is the number of *degrees* of a given node, that is, the number of direct connections to other nodes (Goyal 2007, 12). We may think of the maven as creating these links. In the example, the link between mavens Darby and Newcomen increases the average number of degrees from 1.6 to two.

Let us move fifty years toward the present. We may characterize Birmingham manufacturing in the mid-1770s by the ring network in Figure 3(b). James Watt (WA), a *maven* from the Scottish lowlands, had been able to form strong ties with a native Brummie, Matthew Boulton (B). But Boulton was a true *connector*, a man with fingers in many pies. He introduced Watt to a fellow manufacturer, John Wilkinson (WI), who had just developed a technology for boring cannons accurately. As a result, Watt could achieve the precision that he required to assure that the cylinders of his engines used energy more efficiently than the conventional Newcomen machines. It was Wilkinson in turn who purchased one of the first Boulton and Watt steam engines to be used for his blast furnace at New Willey in Shropshire (Marsden 2002, 100). The dotted line from WA to WI shows how the addition of an extra link in a ring network could considerably improve the efficiency of information flows.

There are two other dimensions of interest for the study of networks. One such feature is the *distance* between two nodes, as measured by the number of connections in the shortest path between them (Goyal 2007, 15). In the ring lattice of Figure 3(a), the average distance is 1.5. As Duncan Watts and Steven Strogatz showed, the addition of random links to a ring lattice reduces the average length of the path between nodes (Watts, et al., 1998). For example, WA-WI, the tie from Watt to Wilkinson in Figure 3(b) reduces the average distance to 1.4. At the same time, the average degree rises from 2 to 2.4.

Yet another characteristic of networks is the tendency for *clusters* to form when connections are added (Goyal 2007, 19). In Figure 3(a), there is no clustering, since the immediate neighbors of a given node are not neighbors of each other. However, in 3(b), nodes WA, B and WI form a cluster. For each of these nodes, two of its neighbors are neighbors of each other. Such clustering is a general feature when random links are added to a ring network (Watts, et al., 1998).

In a seminal paper, Mark Granovetter proposed a seemingly paradoxical concept, namely, the strength of weak ties (Granovetter, 1973). An innovation, he suggested, is more likely to be introduced into a group by marginal members who have bridges to other groups rather than by those belonging to a closely knit cluster. His explanation was that those with weak ties are much more likely to have access to new information from outside than those whose circle of associates is tightly circumscribed. One of the striking features of Figure 2 was the number of innovations in the Manchester area between 1800 and 1849. During the eighteenth century, only 5 percent of the 44 British innovations had come from this region. However, 41 percent of the 32 new British technologies of the first half of the nineteenth century originated near Manchester. Also striking is the small proportion of cooperative breakthroughs in this region. Whereas in the rest of Britain, four-fifths of the innovations during this third half century were cooperative, less than a quarter of those in the Manchester region resulted from cooperation.

The notion of the strength of weak ties is illustrated in Figure 3(c) which portrays in schematic form the networks of the machinery sectors of London and Lancashire. Henry Maudslay, the salesman for a radical new way of producing metal products, is represented by the point M in the cluster on the left. In London, he and his partners and former apprentices formed a closely-tied network. Isambard Kingdom Brunel (BIK), the son of his former partner, Marc Brunel (BM), trained at Maudslay’s Lambeth works. In addition, Maudslay’s partner Joshua Field (F) worked with the younger Brunel on his steamship, the *Great Western*, which ran on a Maudslay steam engine. Meanwhile the two Brunels and Maudslay collaborated on the Thames tunnel, while Marc Brunel recommended Maudslay’s former draftsman, Joseph Clement (C), to Charles Babbage for the construction of his difference engine, ancestor of the computer (Schaffer, 2007).

How can we explain the low willingness to cooperate combined with the striking originality of the nineteenth-century Manchester innovators? Of the 13 important

Manchester innovations during this period, nine were by men who had done their apprenticeship in London with Henry Maudslay (M); namely, Richard Roberts (R), Joseph Whitworth (W) and the Scot, James Nasmyth (N). It would appear that these engineers did not require close ties with people in the region, because they had weak ties to ideas circulating in London. Only one of the three, Joseph Whitworth, was originally from the Manchester area. Their originality came from their ability to combine the latest principles in machine-tool technology with the practical problems of manufacturers in this region of rapidly-expanding industrial production. Note that it was Whitworth, a connector, who persuaded British machine tool makers to adopt a common standard of thread (Rolt 1965/1986, 120-126).

We see, then, that Gladwell's three archetypes have equivalents in the theory of networks. The effect of the maven, who wishes to share his expertise with his neighbors, is to increase the number of degrees, the average number of links for each node. As for the connector, his influence in bringing together people who do not know one another may be measured by the average distance between nodes. Finally, the impact of the salesman, who convinces others to adopt a new technology, may be measured by the importance of clustering, the number of neighbors of each node that are themselves neighbors.

In the next section, we will attempt to find empirical counterparts of these three networking dimensions in order to determine their importance in the innovation process.

IV. Empirical Specification and Data

As we saw in the introduction, Douglass North (1981, 1990) and Joel Mokyr (2009) have explained the Industrial Revolution by forces on the *supply* side, particularly, the appearance of new institutions and new ways of thinking in Britain after 1700. Strongly disagreeing, Robert Allen argued that the most important explanation for British innovations in the eighteenth century was on the *demand* side. Factor endowments – specifically Britain's scarce labor and abundant energy in the form of coal – provided a powerful incentive to substitute coal-powered machinery for labor (Allen 2009). Additional influences on the demand side were the size of Britain's domestic market and its openness to foreign trade. The question is whether these influences alone can explain the timing and vigor of the wave of innovation and the fact that Britain shared it with its American offshoot and also with France – but not with the rest of the world. The preceding section proposed a "social-networks" model of innovation that emphasized changes in people's willingness to collaborate with strangers. This section will present tests of these three approaches to be carried out on a cross-section of data for 201 regions of the North-Atlantic economy over the period from 1700 to 1849.

Let us look first at the dependent variable. In an earlier paper, Allen (1983), followed by Nuvolari (2004), noted that innovations within a given country were not spread evenly across its territory but rather tended to cluster around a few centers. This finding suggests that the unit of observation should be a region within a state. Accordingly, we use count data that measure the number of innovations that occurred in the urban regions if our sample during each fifty-year sub-period between 1700 and 1849. Recall from Section II that each of the 117 innovations was selected from innovations proposed by four historians of technology. We assume that the probability of an innovation in the region of a given city was independent of the number of innovations near other cities in the same period.[8]

[8] A Poisson distribution is appropriate:

$$y_{ijt} = e^{X_{ijt}\beta_i + \varepsilon_{ijt}}, \qquad (1)$$

Consider next some possible explanatory variables. Here the choice depends on the hypothesis being tested. A first group of variables captures the supply-side approach. As mentioned, North (1981, 1990) and Mokyr (2002, 2009) emphasized institutions and new ways of thinking in explaining the remarkable wave of innovation in Great Britain in the latter half of the eighteenth century and the first half of the nineteenth. North and Weingast (1989) suggested that controls on the taxing powers of the sovereign favored the protection of property rights. Mokyr (2009) argued that the British Enlightenment was unique in emphasizing the search for solutions to practical problems. Let us then assume that during this period, Great Britain had certain distinct institutions and cultural characteristics whose effects may be picked up by dummy variables. Accordingly, the variable *Britain* represents Great Britain, while *1750* and *1800* correspond to the half-centuries after 1750 and 1800 respectively.

A second group of variables picks up the influence of demand conditions. Allen (2009) argued that the presence of abundant coal provided a strong incentive to substitute coal for wood as a source of heat and mechanical energy for water, wind and animal power (Allen 2009, 80-105, 172-173). Thus the dummy variable *Factor prices*, indicating the presence or absence of coal within a radius of 30 miles (50 km) of the region's main town, could be expected to have a positive effect on the innovation rate. In addition, the incentive to develop new products and processes depends on the size of the domestic market. Accordingly, one of our geographic explanatory variables will be *Domestic market*, as measured by the country's population. For most cities in the sample, this variable was assumed to be captured by the population within the boundaries of the corresponding present-day state at the beginning of each period. The United States was an exception. At the beginning of the first two sub-periods, the thirteen colonies were a part of the British Empire. Even after the American War of Independence, the two countries remained important trading partners. At the end of the eighteenth century, over half of British exports and a third of its imports were with the Americas, including a

---

where y_{ijt} is the number of innovations in city *i* of type *j* in period *t*, X_{ijt} is a vector of explanatory variables, β_i is a vector of parameters and ε_{ijt} is a random variable.

small portion with British North America (Deane and Cole 1962, 62). Accordingly, Great Britain and the United States will be assumed to form a single market. For many products, access to foreign markets was important. Another indicator of market conditions, therefore, is the degree of openness of the region. This consideration will be captured by the dummy variable *Foreign Markets* indicating whether or not the region's principal city was an ocean port.

The "social-networks" approach of the preceding section posited that there were three dimensions of social networks that could influence the probability of innovation in a given region. One was the *degree* of the network, that is, the average number of links from each node. An explanation often mentioned for the success of Birmingham in attracting the metal industry before 1700 was the freedom from guilds and a municipal corporation. A more flexible, open local social structure free of corporative restrictions allowed people to form associations more easily. The variable *Local openness* was therefore set at one for those British towns that were not boroughs, that is, towns that were not corporations set up under royal charter.

The one French city that had an open and flexible local culture comparable to that of Birmingham in the eighteenth century was Lyon. Since the fifteenth century, it had been the most important publishing center in France. Along with the port of La Rochelle, Lyon was one of the centers of French Protestantism until the repressions of the 1570s. In 1595, the power of local elites was constrained by the Edict of Chauny of Henri IV (Lyon, 2012). Henceforth, the city was to be governed by four aldermen and a provost elected every two years by assemblies of guild masters, subject to royal approval (Lyon, 2012). In the seventeenth and eighteenth centuries, abuses of power were further constrained by a credible threat of revolt on the part of the city's textile workers. During the Revolution of 1789, the city formed a moderate Girondin government until it was crushed by the forces of the Convention. Accordingly, in the case of Lyon, *Local openness* was set at one. For all other towns, including those outside Britain, this variable was set at zero.

Another condition favoring innovation was a shortening of the average distance between nodes, as measured by the number of links in the shortest path between them. With an oral communications technology, the accepted means of contacting a stranger was by personal contact through mutual friends. Under these conditions, social networks were necessarily limited in size. In a literate society, however, newspapers, pamphlets and letters offered a less costly and more rapid means of establishing direct contact with strangers. Accordingly average rates of *Literacy* provide an approximate measure of the average distance between nodes in a society's social network.

It was also suggested that the presence of weak ties between clusters in a network may strengthen the circulation of information between clusters. If each region has its own dialect, information may circulate only with difficulty between regional clusters. As a national language becomes standardized over a larger area, there will be an increase in the number of weak ties between regional clusters. The number of years since a country's language became standardized, *Language standardization*, therefore provides an approximate measure of the strength of "weak ties" between regional clusters in the nation's social network.

Finally, as a regional scale variable for each of the alternative hypotheses, the number of innovations in a region was allowed to change with the population of its main city or town, *City population*.

Data Sources

Number of Innovations. The inventions are listed in Appendix A. the corresponding cities Table 1.

Coal. The proximity of coal deposits for each city was obtained from Barraclough (1984: 201, 210-211).

City population. Population estimates for 201 European cities, each of which had at least 7,000 inhabitants in 1700, were from Bairoch et al. (1988). Of this set, there were 46 cities at or near which one or more innovations occurred. To these, were added the 155 other European cities that were at least as close to London as the most distant innovating city (Como, in northern Italy). Also included were three American cities – New York, Philadelphia and Boston. The city list appears in the Appendix.

Local openness. Data on British municipal charters were obtained from Weinbaum (1943, xxx ff.).

Literacy. Sources of literacy rates in 1700, 1750 and 1800 were: England, Cressy ((Graff 1991)80, 177); France, Graff (1991, 193); Germany, Graff (1991, 187); Italy, Graff (1991, 191); Netherlands, Graff (1991, 223); United States, Graff (1991, 249). The rates for Austria were estimated from the German rate less the German-Austrian difference in 1850 from Cipolla (1969, 115). Estimates for Belgium and Scotland were calculated in the same manner from the 1850 rates for Germany and England respectively.

Lanuage standardization. In order for an entrepreneur to succeed in publishing a unilingual dictionary, he or she had to be confident that there were many citizens in the country who not only were literate, but also sought to master a single standard of spelling and uniform definitions. Even a national government had to take account of the number of potential speakers before subsidizing the publication of a dictionary. This concept is therefore assumed to be captured by the number of years since the publication of the nation's first monolingual dictionary as of the year 1700, based on the data in Figure 4. For example, the entry corresponding to Britain, for which the first dictionary dates from 1658, is 1700-1658 = 42. Similarly, for France, the number was be 1700-1680 = 20, since the first French dictionary appeared in 1680.[9]

INSERT FIGURE 4 ABOUT HERE.

For three countries, the dates of the first dictionary were assigned arbitrarily. The year chosen for Switzerland was the mean of those of France and Germany, while for

[9] Sources. Britain: Howard Jackson, *Lexicography: An Introduction*, 2002, Routledge, London, p. 36; France: Laurent Bray, *César-Pierre Richelet (1626-1698): Biographie et œuvre lexicographique*, Max Niemeter, Tübingen, 1986, pp. 235-242; Germany: Wolfgang Ullrich Würzel, *Konrad Duden*, VEB Bibliographisches Institut, Leipzig, 1985; Italy: Anna Laura Lepschy and Giulio C. Lepschy, *The Italian Language Today*, Second Edition, Routledge, London, p. 24; United States: Jonathon Green, *Chasing the Sun: Dictionary makers and Dictionaries They Made*, Henry Holt, New York, 1996, 290.

Belgium, the year was the mean of those for France and the Netherlands. In the case of the United States, by the end of the eighteenth century, its pronunciation and vocabulary were beginning to diverge from that of Britain, as indicated by the publication of its first dictionary in 1798. Accordingly, its date was set the mean of 1798 and the date for Britain (1658), i.e. 1728.

Country population. The source was Maddison (2007).

V. Results

As explained in the previous section, there are three principal sets of explanations for accelerated innovation in the West after 1700, one emphasizing supply-side factors, a second pointing to forces on the demand side, and a third focusing on social networks. This section presents the results of tests of these hypotheses.

Figure 5 summarizes the statistical results for all 117 innovations. The *t* statistics measure the degree of statistical significance of the various possible influences on innovation. The bars whose length is greater than 1.98 correspond to variables that are significantly greater than zero at the five percent level under a two-tailed test; that is, there is less than one chance in 20 that the hypothesis of a zero effect would be rejected if it were true.

INSERT FIGURE 5 ABOUT HERE.

Looking at the different theories one by one, we see that the supply-side approach has little explanatory power. Other things being equal, *Britain*, with its institutions protecting private property and practical bent was no more innovative than other regions. Moreover, the half-century of the Enlightenment, beginning in *1750*, was no more favorable to innovation, when one controls for other factors, than the preceding or following fifty years. Accordingly, the increase in the propensity to innovate would seem to have been more widely spread, both over space and through time, than is sometimes thought.

There is, however, strong evidence in support of Robert Allen's thesis that relative factor prices were important. Regions that were well endowed with cheap energy in the form of coal (*Factor prices*) were much more likely to innovate. Surprisingly, when one examines the two geographic variables mentioned in almost every discussion of the Industrial Revolution, neither had a significant effect. Other things being equal, *Domestic market* was not a crucial factor in explaining innovation. This finding helps explain why despite their large populations, the German Empire and its successor, the German Confederation, contributed so few new technologies prior to 1850. Nor was a region's openness to external trade, as measured by access to the sea (*Foreign markets*), of any importance. We begin to understand why the Netherlands is absent from Table 1.

The final three variables correspond to the social-networks approach. First is the impact of the variable that captures the flexibility and openness of an urban region's culture when there was no municipal corporation (*Local openness*). We see that statistically this is the most significant of the explanatory variables. The absence of a corporative municipal organization and guild system was a distinct advantage in allowing first Birmingham and later Manchester to stand at the forefront of industrial innovation in the period studied. Similarly, in Lyon, a municipal structure in which the local elite were constrained by the need for royal approval and by a credible threat of worker revolt meant that the city was relatively open to new ideas.

Another strongly significant factor was the degree of *Language standardization*, as measured by number of years since the appearance of the nation's first privately-published monolingual dictionary, as of 1700. The results indicated that the greater the number of years since the appearance of the first such dictionary, the greater the number of innovations. Britain and France had a head start of a century over their rivals in creating vast networks of agents speaking and reading in a standard vernacular tongue. It was arguably this free circulation of ideas from a large number of sources that permitted the conceptual integration that Fauconnier and Turner have suggested is crucial to innovation (Fauconnier and Turner, The Way We Think: Conceptual Blending and the Mind's Hidden Complexities 2002, 183-187). This result also serves to explain why market size was not significant in our results. It was not the number of consumers that was crucial in the process of innovation, but rather the number of people able to interact in a common tongue.

In short, there is strong evidence in support of Robert Allen's thesis that relative *Factor prices* were important. Regions that were well endowed with cheap energy in the form of coal were much more likely to innovate than those that did not. This result helps explain with the English Midlands, with abundant coal performed so well in innovating. Nevertheless, this approach would appear to be incomplete, since other regions of Britain with abundant coal, such as the north-east, Scotland and Wales contributed few innovations.

We saw in Figure 2 that there appeared to be an important difference between cooperative innovations (those with multiple inventors) and non-cooperative innovations (those with a single inventor). During the eighteenth century, Birmingham's success was linked to its ability to foster cooperative innovations. By the nineteenth century, however, neighboring Manchester's success depended largely on non-cooperative innovations. Moreover, the only three countries that were able to develop cooperative innovations (Britain, France and the USA) went on to account for 95 percent of all innovations. In Figure 6, we inquire whether the requirements for the two types of innovation differ. As the two asterisks indicate, literacy and language standardization were significantly more important for cooperative innovations than for non-cooperative innovations.

INSERT FIGURE 6 ABOUT HERE.

This result helps explain why countries without a standardized language (Germany and Italy) or with a small number of native speakers (Austria, Belgium, Denmark, the Netherlands and Switzerland), were unable to generate enough cooperation to develop multiple-inventor innovations. Yet even lone inventors depend on cooperation from suppliers and clients. Without a high willingness to cooperate in the society as a whole, it was difficult for these countries to produce single-inventor innovations.

VI. Implications for the Great Divergence

What are the implications of our results for the debate over the Great Divergence? This section discusses whether China's inability to satisfy the four conditions found statistically-significant for the West can help explain that country's failure to innovate during the modern period.

Consider first factor prices. We found that many innovating regions in Europe had a high price of labor relative to coal. Pomeranz (2000, 62-66) argued that since China's major coal deposits were in the north while its industry was in the south, it was at a factor-price disadvantage relative to Britain, which had cheap coal and expensive labor. However, data presented by Allen (2009b, 532) show that until the mid-eighteenth century, agricultural productivity and therefore real wages were higher on the coast of central China than in England. Accordingly, at the beginning of the period we have studied, the Yangze delta does not seem to have been at a cost disadvantage relative to London, which had to import coal from distant fields in the north-east of England. Moreover, a supposedly high price of coal relative to labor had not prevented China from largely replacing charcoal with coke in the smelting of iron by the eleventh century (Ebrey, 1996, 144). Finally, if factor prices were the key incentive to innovate, why was there no innovation in the modern period near the coalfields of northern China, as there was in the corresponding regions of Birmingham and Manchester?

Turn now to the factors favoring communication within local social networks. The power of the state was much greater during the later Ming and Qing dynasties than it was in England. By the sixteenth century there were over 100,000 scholar-bureaucrats in China (Ebrey 1996, 199). Moreover, particularly in the south, kinship groups placed additional restrictions on individual freedom (Ebrey 1996, 207). As a result, it would have been considerably more difficult in China than in the West for two strangers to collaborate on a new technology without interference from the state or their communities.

Another obstacle to such collaboration was China's low literacy rate. Age-heaping is a tendency of uneducated people to round off their ages, stating their age as 50 rather than 49 or 51. Using this measure, Baten et al. (2010, 355) have estimated that Chinese literacy rates in the nineteenth century were at an intermediate level between those of northern and southern Europe. Even then, there is a difference between reading a popular novel and understanding a technical text. It would seem unlikely that most Chinese readers able to count to 100 had mastered the four thousand characters required to be considered educated.[10] In contrast, Europeans needed to learn only a few dozen

[10] In a comparison of 25 Chinese dynastic histories written before 1950, Cheng (2000, 111-112) found that each contained between 4,000 and 8,000 different characters.

characters to have access to technical literature. Boulton, Watt and other members of the Lunar Society in Birmingham with only a secondary education were able to follow debates on important scientific issues of the day (Uglow 2002).

A final consideration is linguistic standardization. Across the northern plain of China in the eighteenth century, people spoke dialects of Mandarin, most of which were mutually intelligible. However, in the south, the other "dialects" showed much greater variation. As different from each other as French, Spanish and Italian, they were generally not mutually intelligible (Crystal 1997, 314). In conversation, educated people from different regions used "official speech", a version of Mandarin spoken by the imperial court that was never formalized (Ebrey 1996, 304). Even so, increasing differences in pronunciation due lo linguistic drift often led to problems of comprehension. In the early eighteenth century, the Qing emperors established Correct Pronunciation Academies in a vain attempt to improve the Mandarin spoken by officials from the south (Peterson 1997, 104).

The situation in the West in the early eighteenth century was quite different. Although in 1700, there were still differences in pronunciation between the capital and the provinces in Britain and northern France, the vernacular languages had become standardized in both written and spoken form. In Dudley (2012, 177-182), the author has suggested that this linguistic standardization may have served as a signal of willingness to cooperate (Dudley 2012, 177-182). At the very least, it facilitated coordination (Dudley 2012, 185-191).

In short, this comparison of the West and China suggests a crucial reason why China fell behind in innovation during the modern period: without a phonetic written base, its spoken "dialects" drifted ever farther apart from one another over time. Consequently, language as a signal of willingness to cooperate and as a means of coordination was becoming weaker in the East at the same time that it was strengthening in the West.

VII. Conclusion

What, if anything, was different about Western innovation during the period 1700-1850, compared to what was occurring in other areas of civilization? The answer to this question is summarized in the history of the 1840 steamship *Nemesis*. The technologies it combined implied a *rate of innovation* that greatly exceeded that of any other contemporary society or indeed any earlier historical period. Its iron hull, watertight bulkheads and two high-pressure sixty-horsepower engines were technologies that had all been developed in the space of a quarter century. Moreover, the production of this ship was the result of a process of *cooperation* among members of a social network that linked the British metropolis, London, with the coal-producing regions whose role Allen (2009) has highlighted.

Before 1850, the three principal characteristics of the social network that produced the *Nemesis* were to be found in only a few urban regions of Britain, northern France and the north-eastern United States. First, the ship itself was produced in Birkenhead, an *unincorporated town* across the Mersey from Liverpool, free from corporation and guild restrictions. Second, the members of this social network were *literate* in an easily-learned writing system in which there was a close correspondence between symbols and sounds. Finally, the members of the social network spoke a *standardized* vernacular that enabled millions of men and women to cooperate with one another. William Laird, owner of the Birkenhead Iron Works and George Forrester, who supplied the steam engines, were both lowland Scots who had been educated in Standard English (Day and McNeil 1996, 412, 463).[11] Despite coming from a small town 435 miles (700 km) north of London, they were able to communicate with officials of the East India Company in the capital in the same everyday language.[12] This model of innovation was unique to the West.

[11] Herman (2001) has described how due to the influence of the Scottish Church, English in the seventeenth century came to replace Scots as the language of instruction in the Scottish Lowlands.
[12] Both men were from Greenock, near Glasgow, where James Watt was also born.

References

Acemoglu, Daron, and James A. Robinson. *Why Nations Fail: The Origins of Power, Prosperity and Poverty.* London, UK: Profile Books, 2012.

Allen, Robert C. "Agricultural Productivity and Rural Incomes in England and the Yangtze Delta, c.1620–c.1820." *Economic History Review* 62, no. 3 (2009b): 525–550.

Allen, Robert C. "Collective Invention." *Journal of Economic Behavior and Organization* 4 (1983): 1-24.

—. *The British Industrial Revolution in Global Perspective.* Cambridge, UK: Cambridge University Press, 2009.

Bairoch, Paul, Jean Batou, and Pierre Chèvre. *The Population of European Cities, 800-1850.* Geneva: Librairie Droz, 1988.

Barraclough, Geoffrey. *The Times Atlas of World History.* Maplewood, NJ, USA: Hammond, 1984.

Baten, Joerg, Debin Mab, Stephen Morgan, and Qing Wang. "Evolution of Living Standards and Human Capital in China in the 18–20th centuries: Evidences from Real Wages, Age-heaping, and Anthropometrics." *Explorations in Economic History* 47 (2010): 347–359.

Bowman, John S. *Columbia Chronologies of Asian History and Culture.* New York, USA: Columbia University Press, 2000.

Cardwell, D. S. L. *Turning Points in Western Technology.* Canton, MA: Science History Publications/USA, 1991.

Cheng, Chin-Chuan. "Frequently-used Chinese Characters and Language Cognition." *Studies in the Linguistic Sciences* 30, no. 1 (2000): 108-118.

Cipolla, Carlo M. *Literacy and Development in the West.* Harmondsworth, UK: Penguin, 1969.

Clark, Gregory. *A Farewell to Alms: A Brief Economic History of the World.* Princeton, NJ: Princeton University Press, 2007.

Crafts, Nicholas. "Explaining the First Industrial Revolution: Two Views." *European Review of Economic History* 15 (2010): 153-168.

Cressy, David. *Literacy and the Social Order: Reading and Writing in Tudor and Stuart England.* Cambridge, UK: Cambridge University Press, 1980.

Crystal, David. *The Cambridge Encyclopedia of Language, Second Edition*. Cambridge, UK: Cambridge University Press, 1997.

Daumas, Maurice. *A History of Technology and Invention, Volume III, The Expansion of Mechanization, 1725-1860.* New York: Crown Publishers, 1979.

Day, Lance, and Ian McNeil. *Biographical Dictionary of the History of Technology.* London, UK: Routledge, 1996.

Deane, Phyllis, and W. A. Cole. *British Economic Growth, 1688-1959 : Trends and Structure.* Cambridge, UK: Cambridge University Press, 1962.

Duchesne, Ricardo. *The Uniqueness of Western Civilization.* Leiden: Brill, 2011.

Dudley, Leonard. *Mothers of Innovation: How Expanding Social Networks Gave Birth to the Industrial Revolution.* Newcastle upon Tyne, UK: Cambridge Scholars Publishing, 2012.

Ebrey, Patricia Buckley. *The Cambridge Illustrated History of China.* Cambridge, UK: Cambridge University Press, 1996.

Eisner, Manuel. "Long-Term Historical Trends in Violent Crime." *Crime and Justice* 30 (2003): 83-142.

Fauconnier, Gilles, and Marc Turner. *The Way We Think: Conceptual Blending and the Mind's Hidden Complexities.* New York: Basic Books, 2002.

Fauconnier, Gilles, and Mark Turner. "Rethinking Metaphor." In *Cambridge Handbook of Metaphor and Thought*, by R. Gibbs, 53-66. New York: Cambridge University Press, 2008.

Gladwell, Malcolm. *The Tipping Point: How Little Things Can Make a Big Difference.* New York: Little Brown, 2000.

Goyal, Sanjeev. *Connections: An Introduction to the Economics of Networks.* Princeton, NJ, USA: Princeton University Press, 2007.

Graff, Harvey J. *The Legacies of Literacy.* Bloomington, Indiana, USA: Indiana University Press, 1991.

Granovetter, Mark. "The Strength of Weak Ties." *American Journal of Sociology* 78 (1973): 1360-1380.

Harris, Martin. "French." In *The World's Major Languages*, by Bernard Comrie, 210-235. Oxford, UK: Oxford University Press, 1990.

Headrick, Daniel R. *The Tools of Empire: Technology and European Imperialism in the Nineteenth Century.* Oxford, UK: Oxford University Press, 1981.

Herman, Arthur. *How the Scots Invented the Modern World.* New York: Three Rivers Press, 2001.

Jones, Eric L. *The European Miracle.* Cambridge, UK: Cambridge University Press, 1981.

Koestler, Arthur. *The Act of Creation.* London: Hutchison & Co., 1964.

Lyon. "Décembre 1595: Publication de l'Edit de Chauny." *Archives municipales.* 2012. http://www.archives-lyon.fr/archives/sections/fr/histoire_de_lyon/archives_commentees/les_personnages/henri_iv2935/1595_edit_chauny/.

Maddison, Angus. *Contours of the World Economy, 1-2030 AD: Essays in Macro-Economic History.* Oxford, UK: Oxford University Press, 2007.

Marsden, Ben. *Watt's Perfect Engine: Steam and the Age of Invention.* New York: Columbia University Press, 2002.

Mokyr, Joel. *The Enlightened Economy: An Economic History of Britain 1700-1850.* New Haven, USA: Yale University Press, 2009.

—. *The Gifts of Athena : Historical Origins of the Knowledge Economy.* Princeton, NJ: Princeton University Press, 2002.

—. *The Lever of Riches: Technological Creativity and Economic Progress.* Oxford, UK: Oxford University Press, 1990.

Needham, Joseph. *Science and Civilisation in China, Volume 4, Physics and Physical Technology, Part II, Mechanical Engineering.* Cambridge, UK: Cambridge University Press, 1965.

North, Douglass C. *Institutions, Institutional Change, and Economic Performance.* Cambridge, UK: Cambridge University Press, 1990.

—. *Structure and Change in Economic History.* New York: Norton, 1981.

North, Douglass C., and Barry R. Weingast. "Constitutions and Commitment: The Evolution of Institutions Governing Public Choice in Eighteenth Century England." *Journal of Economic History* 49 (1989): 803-832.

Nuvolari, Alessandro. "Collective Invention during the British Industrial Revolution: The Case of the Cornish Pumping Engine." *Cambridge Journal of Economics* 28, no. 3 (2004): 347-363.

Ophir, Eyal, Clifford Nass, and Anthony D. Wagner. "Cognitive Control in Media Multitaskers." *Proceedings of the National Academy of Sciences* 106, no. 37 (2009): 15583-15587.

Pashler, Harold. "Dual-Task Interference in Simple Tasks: Data and Theory." *Psychological Bulletin* 116, no. 2 (1994): 220-244.

Paulinyi, Akos. *Industrielle Revolution: Vom Ursprung der modernen Technik.* Reinbek bei Hamburg, Germany: Rowohlt, 1989.

Percy, J. *Metallurgy: Iron and Steel.* London: John Murray, 1864.

Peterson, Glen. *Power of Words: Literacy and Revolution in South China, 1949-96.* Vancouver, Canada: UBC Press, 1997.

Pomeranz, Kenneth. *The Great Divergence: China, Europe, and the Making of the Modern World Economy.* Princeton, NJ, USA: Princeton University Press, 2000.

Rolt, L.T. C. *Tools for the Job: A History of Machine Tools to 1950.* London, UK: Her Majesty's Stationery Office, 1965/1986.

Rosen, William. *The Most Powerful Idea in the World: A Story of Steam, Industry, and Invention.* New York: Random House, 2010.

Schaffer, Simon. "Babbage's Intelligence." *Imaginary Futures.* April 16, 2007. http://www.imaginaryfutures.net/2007/04/16/babbages-intelligence-by-simon-schaffer/ (accessed November 30, 2011).

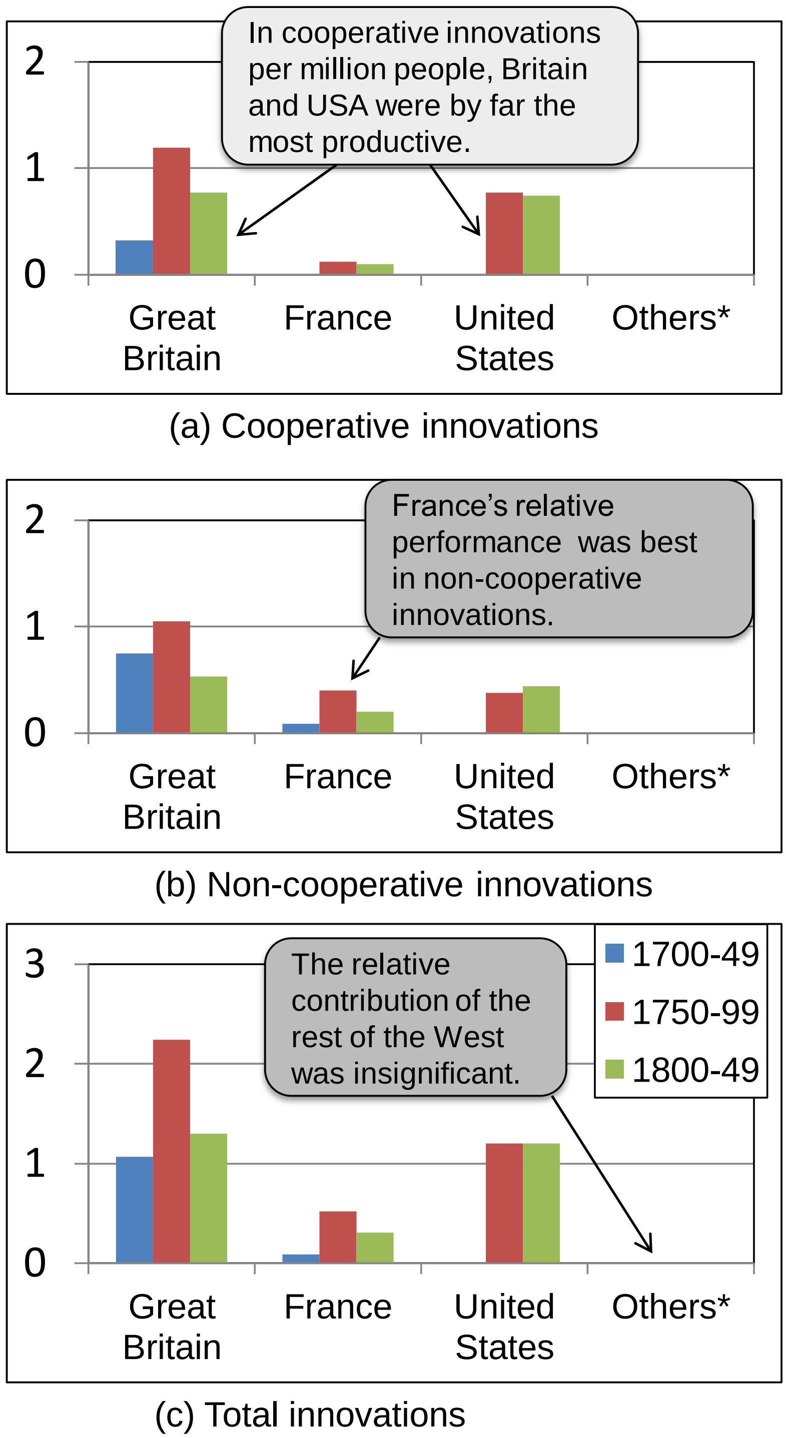
Temple, Robert. *The Genius of China: 3,000 Years of Science, Discovery, and Invention.* New York, USA: Simon & Schuster, 1986.

Uglow, Jenny. *The Lunar Men: Five Friends Whose Curiosity Changed the World.* New York: Farrar, Straus and Giroux, 2002.

Vries, Jan de, and Ad van der Woude. *The First Modern Economy: Success, Failure, and Perseverence of the Dutch Economy, 1500-1815.* Cambridge, UK: Cambridge University Press, 1997.

Watts, Duncan J., and Stephen H. Strogatz. "Collective Dynamics of Small World Networks." *Nature* 393 (1998): 440-442.

Weinbaum, Martin. *British Borough Charters, 1307-1660.* Cambridge, UK: Cambridge University Press, 1943.



* Austria, Belgium, Denmark, Germany, Luxembourg, Netherlands, Switzerland

Figure 1. Innovations per million inhabitants, 1700-1849

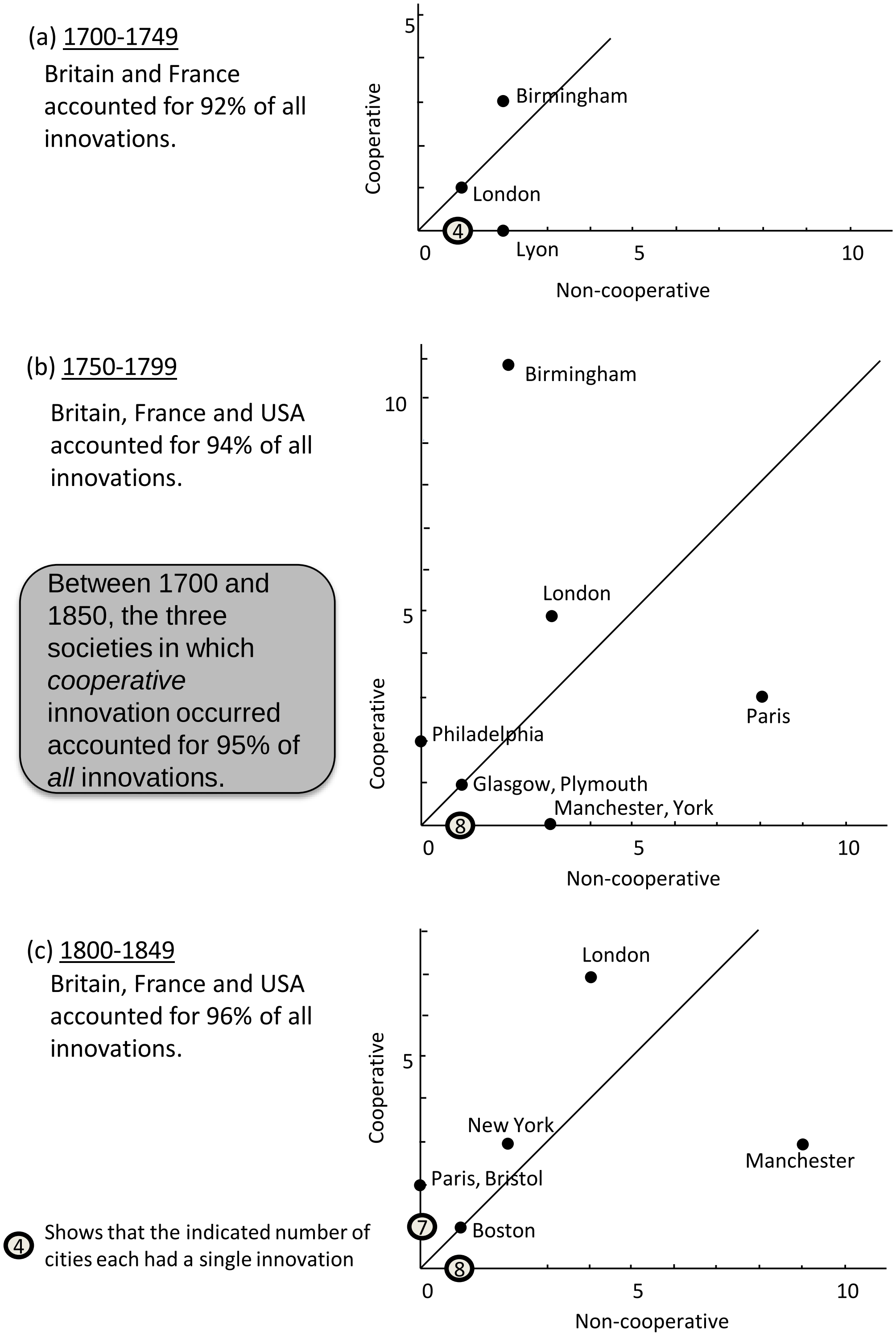


Figure 2. Timing and location of 117 innovations, 1700-1849

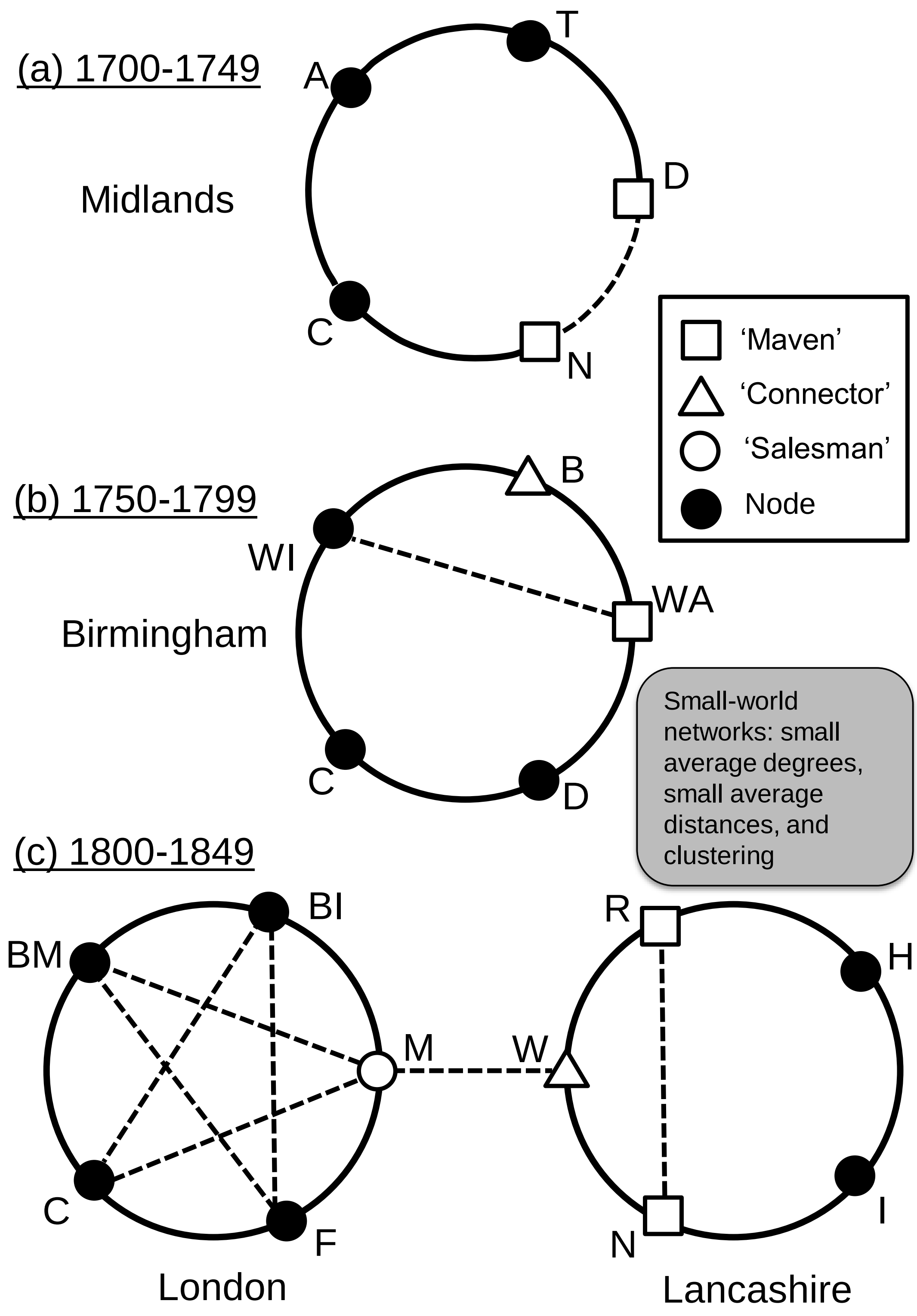


Figure 3. Small-world networks

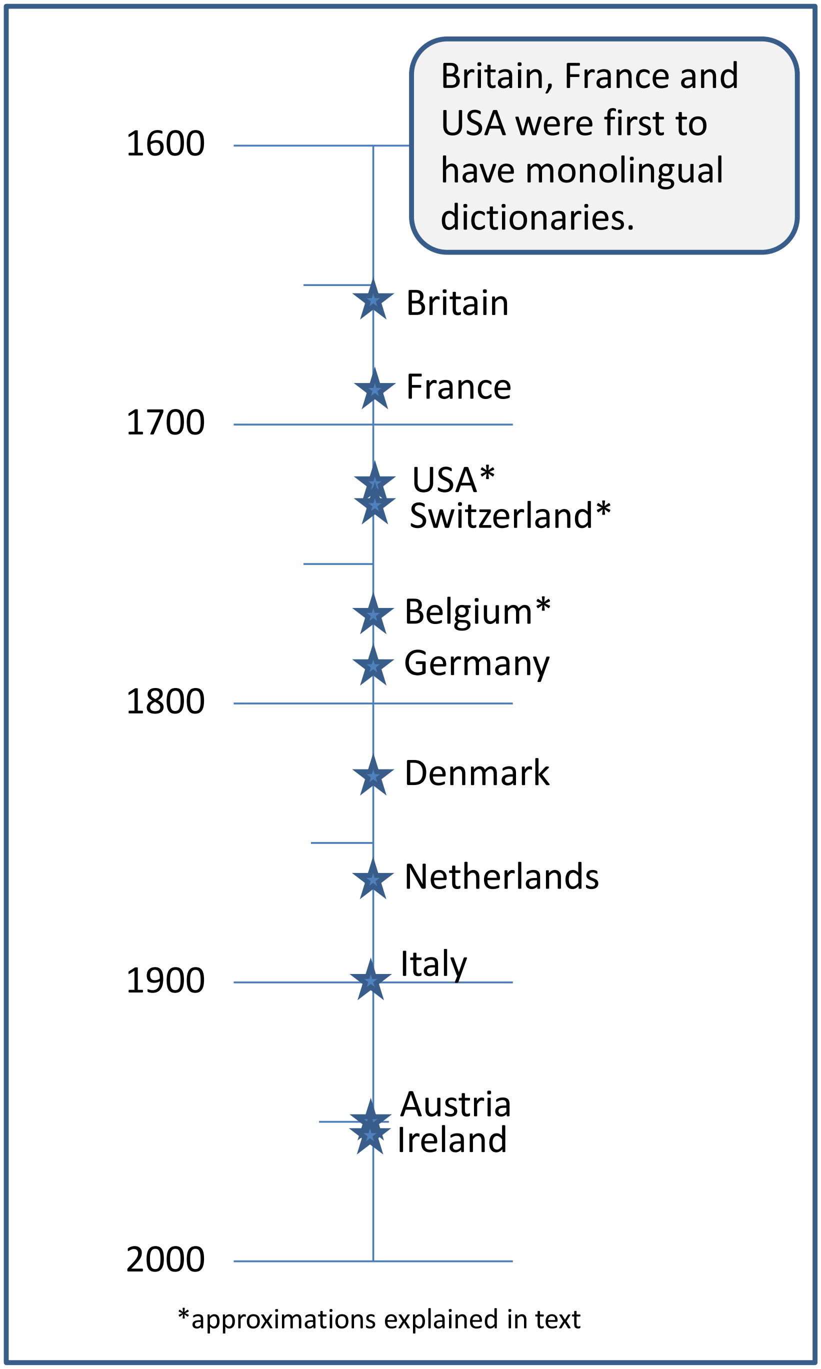
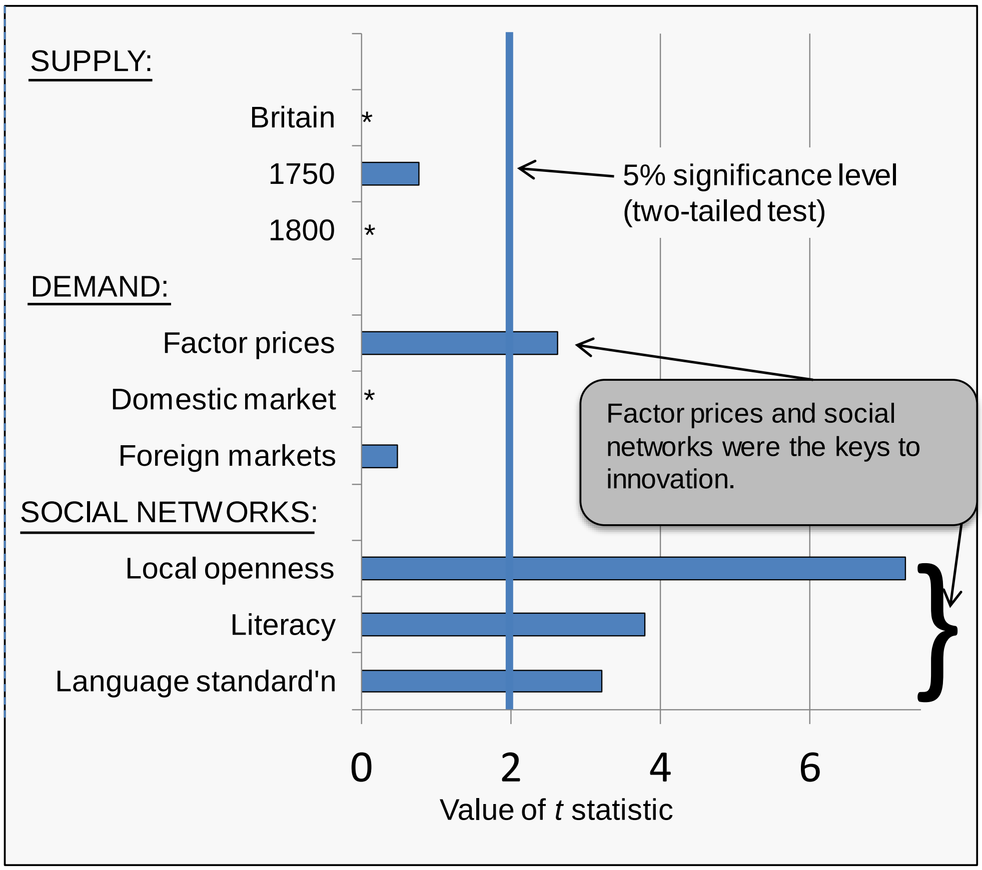
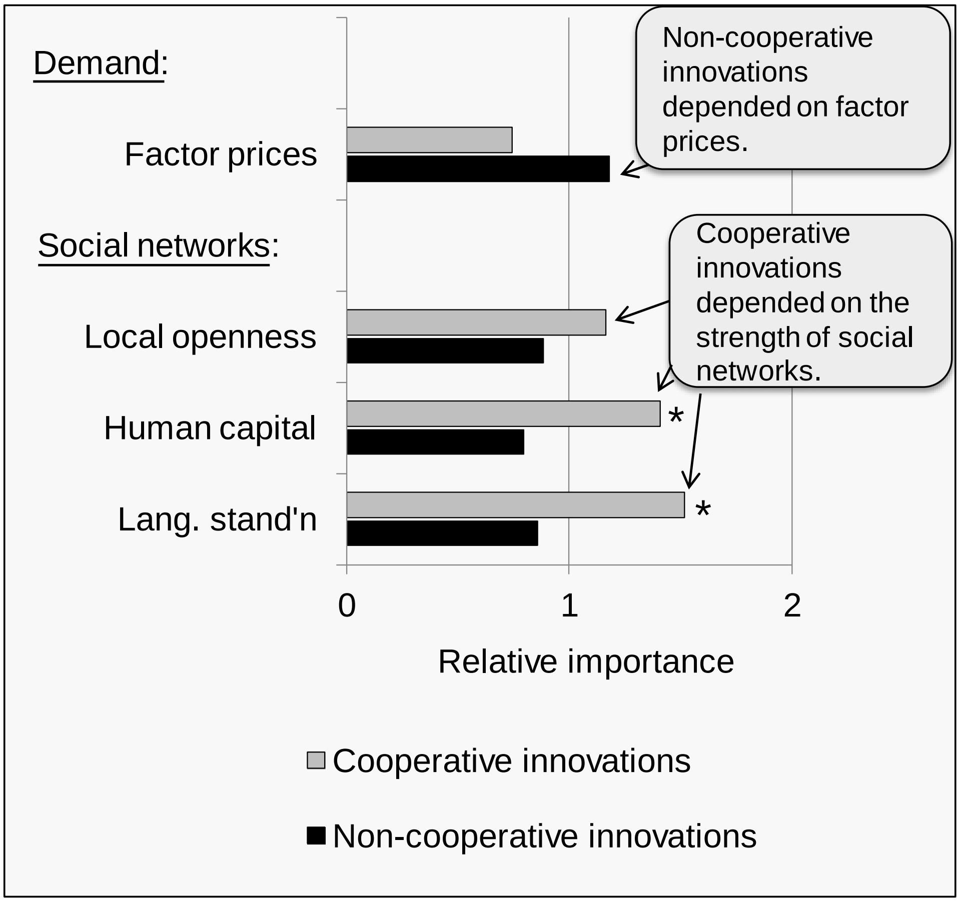


Figure 4. Year of first monolingual dictionary



* negative and statistically insignificant

Figure 5. A test of theories of innovation with 1700-1849 data



* Difference significant (5%, one-tailed test)

Figure 6. Relative importance of several influences on innovation rates, by type of innovation

Appendix A
Locations of 117 important innovations, 1700-1849

Country	1700-1749	1750-1799	1800-1849
Denmark			Galvanometer (Copenhagen, 1819)
France	Loom coded with perforated paper (Lyon, 1725) Loom coded with punched cards (Lyon, 728)	Steam-powered wagon (Paris, 1770) Automatic loom (Paris, 1775) Single-action press (Paris, 1781) Two-engine steamboat (Lyon, 1783) Hot-air balloon (Paris, 1783) Parachute (Montpellier, 1783) Press for the blind (Paris, 1784) Chlorine as bleaching agent (Paris, 1785) Sodium carbonate from salt (Paris, 1790) Visual telegraph (Paris, 1793) Vacuum sealing (Paris, 1795) Paper-making machine (Paris, 1798) Illuminating gas from wood (Paris, 1799)	Automatic loom with perforated cards (Lyon, 1805) Wet spinning for flax (Avignon, 1815) Electromagnet (Paris, 1820) Water turbine (Saint-Étienne, 1824) Single-helix propeller (Le Havre, 1832) Three-color textile printing machine (Rouen, 1832) Water turbine with adjustable vanes (Besançon, 1837) Photograpy (Paris, 1838) Multiple-phase combing machine (Mulhouse, 1845)
Germany	Porcelain (Dresden, 1707)	Lithography (Munich, 1796)	
Great Britain	Seed drill (Oxford, 1701) Iron smelting with coke (Birmingham, 1709) Atmospheric engine (Birmingham, 1712) Pottery made with flint (Birmingham, 1720) Quadrant (London, 1731) Flying shuttle (Manchester, 1733) Glass-chamber process for sulphuric acid (London, 1736) Spinning machine with rollers (Birmingham, 1738) Stereotyping (Edinburgh, 1739) Lead-chamber process for sulphuric acid (Birmingham, 1746)	Crucible steel (York, 1750) Rib knitting attachment (Birmingham, 1755) Achromatic refracting telescope (London, 1757) Breast wheel (York, 1759) Bimetallic strip chronometer (London, 1760) Spinning jenny (Manchester, 1764) Creamware pottery (Birmingham, 1765) Cast-iron railroad (Birmingham, 1768) Engine using expansive steam operation (Glasgow, 1769) Water frame (Birmingham, 1769) Efficient atmospheric steam engine (Newcastle, 1772) Dividing machine (London, 1773) Cylinder boring machine (Birmingham, 1775) Carding machine (Birmingham, 1775) Condensing chamber for steam engine (Birmingham, 1776) Steam jacket for steam engine (Birmingham, 1776) Spinning mule (Manchester,	Machines for tackle block production (London, 1800) Illuminating gas from coal (Birmingham, 1802) Steam locomotive (Plymouth, 1804) Compound steam engine (London, 1805) Winding mechanism for loom (Machester, 1805) Arc lamp (London, 1808) Food canning (London, 1810) Rack locomotive (Bradford, 1811) Mechanical printing press (London, 1813) Steam locomotive on flanged rails (Newcastle, 1814) Safety lamp (London, 1816) Circular knitting machine (London, 1816) Planing machine (Manchester, 1817) Large metal lathe (Manchester, 1817) Gas meter (London, 1819) Metal power loom (Manchester, 1822) Rubber fabric (London, 1823) Locomotive with fire-tube boiler (Manchester, 1829)

Country	1700-1749	1750-1799	1800-1849
		1779) Reciprocating compound steam engine (Plymouth, 1781) Sun and planet gear (Birmingham, 1781) Indicator of steam engine power (Birmingham, 1782) Rolling mill (London, 1783) Cylinder printing press for calicoes (Glasgow, 1783) Jointed levers for parallel motion (Birmingham, 1784) Puddling (London, 1784) Power loom (York, 1785) Speed governor (Birmingham, 1787) Double-acting steam engine (Birmingham, 1787) Threshing machine (Edinburgh, 1788) Single-phase combing machine (York, 1789) Machines for lock production (London, 1790) Single-action metal printing press (London, 1795) Hydraulic press (London, 1796) High-pressure steam engine (Plymouth, 1797) Slide lathe (London, 1799)	Hot blast furnace (Glasgow, 1829) Self-acting mule (Manchester, 1830) Lathe with automatic cross-feed tool (Manchester, 1835) Planing machine with pivoting tool-rest (Manchester, 1835) Even-current electric cell (London, 1836) Electric telegraph (London, 1837) Riveting machine (Manchester,1838) Transatlantic steamer (Bristol, 1838) Assembly-line production (Manchester, 1839) Multiple-blade propeller (London, 1839) Steam hammer (Manchester, 1842) Iron, propellor-driven steamship (Bristol , 1844) Measuring machine (Manchester, 1845) Multiple-spindle drilling machine (Manchester, 1847)
Italy			Electric battery (Como, 1800)
Switzer-land		Massive platen printing press (Basel, 1772) Stirring process for glass (Berne, 1796)	
United States		Continuous-flow production (Philadelphia, 1784) Cotton gin (Philadelphia, 1793) Machine to cut and head nails (Boston, 1795)	Single-engine steamboat (New York, 1807) Milling machine (New York, 1818) Interchangeable parts (New York, 1824) Ring spinning machine (Boston, 1828) Grain reaper (Philadelphia, 1832) Binary-code telegraph (New York, 1845) Sewing machine (Boston, 1846) Rotary printing press (New York, 1847)

Sources: Daumas (1979), Cardwell (1972/1991), Mokyr (1990), Paulinyi (1989).
Cooperative innovations are underlined.

Appendix B
List of cities

Germany: Aachen, Altona, Augsburg, Bamberg, Berlin, Brandenburg, Braunschweig, Bremen, Dresden, Duesseldorf, Emden, Erfurt, Esslingen, Frankfurt am Main, Frankfurt an der Oder, Freiberg, Gotha, Halberstadt, Hamburg, Hannover, Ingolstadt, Kassel, Koblenz, Koeln, Leipzig, Luebeck, Magdeburg, Mainz, Mannheim, Muenchen, Muenster, Naumburg, Nuernberg, Regensburg, Stralsund, Stuttgart, Trier, Ulm, Wuerzburg, Zittau

Austria: Innsbruck, Salzburg, Schwaz,

Belgium: Aalst, Antwerpen, Brugge, Bruxelles, Gent, Ieper, Kortrijk, Leuven, Liege, Lokeren, Mechelen, Mons, Namur, Oostende, Tournai, Verviers

France: Abbeville, Agen, Aix, Albi, Alencon, Amiens, Angers, Arles, Arras, Aurillac, Avignon, Bayeux, Bayonne, Beauvais, Besançon, Beziers, Blois, Bordeaux, Bourges, Brest, Caen, Cambrai, Carcassonne, Castres, Chalons-sur-Marne, Chambery, Chartres, Clermont-Ferrand, Colmar, Dieppe, Dijon, Douai, Dunkerque, Grenoble, La Rochelle, Langres, Laval, Le Havre, Le Mans, Le Puy, Lille, Lyon, Marseille, Mayenne, Metz, Montauban, Montpellier, Moulins, Mulhouse, Nancy, Nantes, Narbonne, Nimes, Orleans, Paris, Poitiers, Reims, Rennes, Rouen, Saumur, Soissons, St-Etienne, St-Malo, St-Omer, St-Quentin, Strasbourg, Toulon, Toulouse, Tours, Troyes, Valenciennes, Versailles, Vienne, Vitry-le-François

Great Britain: Aberdeen, Birmingham, Bradford, Bristol, Cambridge, Colchester, Coventry, Dundee, Edinburgh, Exeter, Glasgow, Great-Yarmouth, Ipswich, London, Manchester, Newcastle-upon-Tyne, Norwich, Oxford, Plymouth, Salisbury, Shrewsbury, Worcester, York

Ireland: Cork, Dublin, Kilkenny, Limerick

Italy: Alessandria, Asti, Como, Milano, Monza, Novara, Pavia, Torino, Vercelli, Vigevano

Netherlands: Alkmaar, Amersfoort, Amsterdam, Delft, Dordrecht, Enkhuizen, Gouda, Groningen, Haarlem, Harlingen, Hoorn, Leeuwarden, Leiden, Maastricht, Middelburg, Nijmegen, Rotterdam, 's Gravenhague, 's Hertogenbosch, Schiedam, Utrecht, Vlissingen, Zwolle

Switzerland: Basel. Bern. Geneve. Zuerich

United States: Boston. New York. Philadelphia