Mothers of Innovation:
How Expanding Social Networks
Gave Birth to the Industrial Revolution

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By

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The spirit of the age affects all the arts; and the minds of men, being once roused from their lethargy, and put into a fermentation, turn themselves on all sides, and carry improvements into every art and science.

—David Hume, *Essays, Moral, Political, and Literary*

PREFACE

The term "Industrial Revolution" was first used in 1799 by the French *chargé d'affaires* in Berlin, Louis-Guillaume Otto, to compare the rapid industrialization occurring in France to the momentous political events of ten years earlier in that country (Crouzet, 1996 p. 45). But the child has now surpassed the parent. A recent Google search yielded almost 500,000 references for the term "Industrial Revolution" compared to only 360,000 for "French Revolution". Yet paradoxically, when France appears in contemporary discussions of the Industrial Revolution, it usually plays the role of a foil designed to emphasize the reasons for British success. In such studies, even the United States is generally seen not as an innovator but rather as a supplier of raw materials for British factories, a market for British manufacturers or an outlet for British capital.[1]

Unfortunately, most of the half million references to the Industrial Revolution mentioned above have asked the wrong question. The phenomenon to be explained is not why Britain was the first country to industrialize, for it is now clear that British industrial growth in the eighteenth century was considerably less rapid than previously thought (Crafts, et al., 1992). Nor is the essential issue why sustained technological progress occurred first in Britain, the question asked in recent volumes by two prominent economic historians, Joel Mokyr (2009) and Robert Allen (2009). As we will see, the tipping point for innovation in Britain occurred

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[1] In his classic study, *The Industrial Revolution*, Thomas Ashton (1948/1962) barely mentioned French inventors, and overlooked the parallel industrialization of the United States. Similarly, Rondo Cameron's (1993) chapter on the Industrial Revolution in his *Concise Economic History of the World* was devoted entirely to Britain (Cameron 1993, 162-190). Exceptionally, Joel Mokyr's 1990 study, *The Lever of Riches*, detailed the numerous contributions of French and American inventors. However, in his more recent survey, *The Enlightened Economy*, he argued that Britain "dominated in developing inventions made at home or elsewhere, putting new ideas to successful commercial use, and finding new applications for them." France, he noted, though larger was less successful in innovating (Mokyr 2009, 399). In a similar vein, Robert Allen, in a chapter of his recent book asking why the Industrial Revolution was British, pinpointed the failed initiatives of the French state (R. C. Allen 2009, 153-154).

at about the same time as in northern France and the United States, namely, in the decades around the year 1800.

The awarding of medals for industrialization to individual nations has diverted attention away from the crucial issue of what was occurring at the regional level *within* national boundaries. The appropriate question, this book will argue, is the following: *why over the century and a half from 1700 to 1850 was there a sharp acceleration in the rate of innovation in certain regions of Britain, France and the United States, but not elsewhere*? It is remarkable that from 1700 to 1850, there was no innovation worthy of note in the Netherlands, initially both richer and more literate than Britain and France. Similarly, Germany, which was much larger (in population) although perhaps not as literate as Britain by some measures, contributed little to the new technologies of this period.[2] It is also surprising that Scandinavia, Belgium, Italy, Spain and the rest of the world's societies played virtually no role in the innovations of this century and a half. Even in Britain, it is not easy to explain why most industrial innovation occurred in a narrow band of territory stretching from London to the previously-obscure inland towns of Birmingham and Manchester. The coastal cities of the south, the west, the north-east and Scotland, which had easier access to foreign resources and markets, proved to be less favorable ground for the seeds of novelty.

In order better to explain the spatial distribution of innovation over the long century and a half after 1700, this study proposes a new approach. First, it examines an aspect of innovation that has hitherto been neglected, namely, the extent of cooperation. To do so, it highlights the communications technologies that helped determine the size of social networks. Second, the study focuses on towns and their hinterland rather than sovereign states, arguing that local cultures and rates of learning varied sharply among regions, even within the same nation. Finally, the preparation of a sample of some 117 innovations, scattered across 201 regions in ten countries (according to current international borders) permits rigorous testing of competing hypotheses. It will be possible to estimate the relative importance for the innovation process of institutions, geography, resource endowments, human capital and circles of cooperation.

***

The present study is an expedition to explore the boundary between past and present. On the far side of this frontier, change was so gradual

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[2] Literacy in this comparison is measured by per-capita book production. See Figure 5-3.

that each generation lived in a way very similar to those that preceded it. But on the near side, transformation has been such a constant presence that children continually encounter situations that their parents have never experienced. Between these two periods, one stretching back into the dark mists of history and the other forward into the shimmering haze of the future, there is a century and a half from the prime of Daniel Defoe (1659-1731) to that of Charles Dickens (1812-1870). During the interval between Robinson Crusoe and David Copperfield, technological innovation, which had previously been episodic and barely perceptible, suddenly became the dominant feature of most people's lives. The changes occurred first in the North-Atlantic community and then spread gradually across the planet. It was in this period that people experienced the shock of a first-time encounter with a smokestack, a factory, a daily newspaper, a steamship, or a locomotive.

Something profoundly new was happening. Today we would call it innovation, but as social historian Peter Borsay (2002, p. 183) has indicated, in the eighteenth century, it would have been termed *improvement*. Indeed, this book's introductory quotation from David Hume expresses the idea clearly. It was the "spirit of the age, affecting all the arts; and the minds of men" – the idea of progress. As Borsay (op. cit. p, 184-185) has explained, this notion of improvement was the central element of the Enlightenment, both in Britain and in France. In addition, the concept had a moral dimension, consisting of norms of behavior that we today might describe as social capital.

In retrospect, the shock that occurred between 1700 and 1850 appears to have been the third variation on a theme. One element of the underlying subject was the expansion of circles of social interaction. As in the very distant past, humans experienced the impact of a widening of the group of individuals with whom they were willing to cooperate. Another element of the theme was a more intense search for things new. A key finding of recent anthropological research is that compared to other primates, *homo sapiens* has been characterized by exceptional degrees of both cooperation and innovation. Consider, for example, the collaborative efforts of Cro-Magnon hunters and tailors that made possible multi-layered clothing capable of resisting the frigid winters of northern Europe some 30,000 years ago (Fagan, 2010 pp. 166-167). Or imagine the social networks required to build and maintain elaborate networks of irrigation canals to water the deserts of the Middle East some 5,000 years ago (Roberts, 1980 pp. 64-65).

The evolution of cooperation and innovation over the 200,000 years of our common history has not been smooth. In the sphere of cooperation, anthropologists have observed a series of discontinuities as people came together in increasingly complex social groupings: from the band to the tribe, then on to the state, and most recently to the culturally-homogeneous nation state (Diamond, 1997 pp. 265-281). There is strong evidence that certain of these social transitions coincided with parallel discontinuities in the sphere of innovation. Consider the development of thin-bladed tools and other new artifacts by hunters in southern Africa about 70,000 years ago (Fagan 2010, 97-99). Some anthropologists believe that these changes coincided with a cooling in climate that forced humans to make a transition from small isolated hunting bands to kinship networks practicing reciprocal information exchange over large areas (Fagan 2010, 100-101). Then reflect on the invention of the wheel, the abacus and metal weapons by the urbanized Sumerians. Or finally, recall the more recent burst of Western inventions – the steam engine, the cotton mill and the locomotive – all developed within the confines of the nation state. In each case, an extension of the circle of *cooperation* appears to have occurred at the same time as acceleration in the rate of *innovation*. Wider sharing and more rapid generation of novelty coincided!

In both of these dimensions – the formation of increasingly complex societies and the development of new technologies – the challenge for social scientists has been to explain how humans managed to solve what are known as Collective-Action Problems – the strategic conflicts that inevitably arise when people interact with one another. One such problem is the Prisoner's Dilemma. Two individuals may together have much to gain by cooperating, but each may do even better if he defects, whatever the strategy of the other player. For example, if four students are assigned a group project, one student may slack off, leaving his team-mates to complete the work. But, expecting their colleague to shirk, the others may also make little serious effort to finish the project.

It is easy to see how this dilemma applies to the formation of a complex society. Two families living close together will have a number of collective dilemmas to resolve. They will have to decide how their limited resources are to be divided between them. In addition, they will have to determine how to protect their assets from theft by their neighbors. It is less obvious how these problems apply to innovation. The image of the lone inventor struggling in his attic comes easily to mind. However, as we will see, in recent times, at least as common has been the picture of two or more individuals struggling together toward a common goal, each bringing talents and knowledge that the others lack. Cooperation in this case was essential. Moreover, even the single inventor was dependent upon the cooperation of other members of his society as suppliers, customers and neighbors.

The Prisoner's Dilemma could easily be resolved if those players who had both a high level of competence and a willingness to cooperate could signal this capacity credibly to one other. Michael Spence argued that signaling of this type is feasible if the cost of sending a message is negatively correlated with the competence and willingness to cooperate of the players (Spence 1973, 358-359). For example if those who are more competent and reliable can more easily complete a program of formal education, then a diploma is a credible signal of ability.

Here it is time to add a third dimension to our discussion of cooperation and innovation, namely, *language*. In southern Africa, some 60,000 to 70,000 years ago, hunter-gatherers appear to have developed an ability to communicate in articulate speech (Fagan 2010, 101). This new linguistic capacity must have greatly reduced the cost of credibly signaling one's capability as a potential partner, provided that language acquisition was less costly for those individuals who were more conscientious. Anthropologists have long speculated about the causes of the extinction of other hominid species such as the Neanderthals who shared the forests of Europe with Cro-Magnon modern humans for thousands of years. Were the Neanderthals slaughtered by hunters with more advanced tools? Or were they less efficient at extracting resources from a given territory. Signaling theory offers an insight: without fully developed language, they would have been able unable to signal their competence to one another as easily as *homo sapiens*.[3] Cooperation between Neanderthal bands would consequently have been much more problematic, and they would have had great difficulty innovating and adapting to change.[4]

Similarly, five thousand years ago, in the first cities in Mesopotamia, the ability to store and retrieve information accurately by use of phonetic symbols would have permitted the construction of a permanent data base

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[3] Brian Fagan has suggested that the greater networking skills of the modern humans enabled them enabled them to adapt better to changes in climate and geography than the Neanderthals could (Fagan 2010, 109).

[4] However, the Neanderthals' lack of articulate speech did not prevent them from mating with our *homo sapiens* ancestors: it is estimated that between one and four percent of the DNA of those who have family origins outside Africa came from these hominid cousins (Wong 2010). Some groups of modern humans also share genes with the Denisovans, another group of hominids closely related to the Neanderthals. A comparison of the genomes of this species and humans indicates that in the past 80,000 years humans have developed at least eight genes associated with language and nerve development (Meyer, 2012).

for the administration of an irrigation network benefiting tens of thousands of inhabitants. The first states could thereby collect taxes from individuals according to the amount of goods they produced and use the receipts to pay laborers according to the amount of work they performed on public projects. As Paul Seabright explained in his study of the evolution of economic interaction, *The Company of Strangers*, the invention of first, the spoken language and later, writing has permitted knowledge to become collective (Seabright, 2004, pp. 176-177).

In late seventeenth-century England and France, there was a similar problem in inducing would-be inventors to work together on a common problem. The difference, compared to the sub-Saharan Africans of prehistoric times or the Sumerians more recently, was that the potential community now numbered in the millions rather than dozens or thousands. For example, a manufacturer with access to capital and knowledge of markets might have been hesitant to back an inventor from a distant region who came to him with ideas about a new technology. The manufacturer would likely fear that the potential partner, about whom he knew little, would take advantage of any resources granted. The inventor in turn would be reluctant to share his potential profits with a financial backer of unknown reputation who might fail to contribute sufficiently to their joint efforts.

This study will argue that the late seventeenth-century equivalent of the appearance of articulate language, or the development of logo-graphic script, was the emergence of a capacity to read and write in standardized versions of vernacular tongues shared by millions of fellow citizens. The challenge for us in this study will be to separate the effects of this new communications technology from other possible influences on the rate of innovation.

The second Collective-Action Problem is one of Assurance. Even if all players can do better by cooperating rather than by defecting, there may be a problem in coordinating their actions. Each may well choose to defect in order to avoid bearing an unfair share of the costs should the others shirk. In the case of prehistoric Europe, even if oral communication was sufficiently well developed to overcome the Prisoner's Dilemma, cooperation would not necessarily have followed.

It seems to have taken a crisis, notably a change in climate or in animal migration patterns, to induce people from different bands to work together. People had to learn to trust one another. Here again, having fully-developed language may have played an important role in allowing people to coordinate their behavior. Fluent speech would have permitted what Joseph Farrell and Matthew Rabin (1996) have described as "cheap talk" –

low-cost information exchange permitting coordination between individuals with common interests.[5] Complex (but inexpensive) messages such as “We will give you ten pieces of good flint provided that you inform us where we can find water while we travel across your territory,” now became possible. As a result, new techniques could be diffused more rapidly. In addition, with enhanced trading possibilities, the raw materials and concepts available for potential innovation were greatly expanded. For example, strong, straight pieces of hard wood from one area could be combined with workable stone from another to produce sharp-tipped spears. In a similar manner, at the beginning of the historical period, it may have required a drought or flood to persuade residents of Mesopotamian villages to work together to build a large-scale irrigation system.

It must have taken considerable evidence that cooperation was advantageous to convince people to make permanent changes in their habits. If so, reports of previous success in overcoming technical challenges may have played an important role in encouraging further innovation. We should therefore be on the lookout for evidence that spillovers over time from key innovations are not merely technological but also behavioral. Having observed successful cooperation around them, people may modify their own habits, becoming more willing to cooperate with strangers.

The goal of this book is to present and test the possibility of causal links running from communications on the one hand to cooperation and innovation on the other. As far as the Paleolithic and Sumerian periods are concerned, any answer must remain speculative. There simply is not enough evidence to determine whether one set of changes was caused by the other or whether both were influenced by a third factor. However, for more recent centuries, we have quite considerable evidence of the circumstances surrounding over a hundred technological innovations, along with detailed records of other possibly-related developments both before and during the Industrial Revolution.

But why around the year 1700 was an *increase* in the willingness to cooperate necessary, along with a complementary *new* communications technology, in order to generate further innovations? After all, medieval Europe had been able to improve technologies developed earlier in Asia; for example, the heavy plow, the horse collar, water mills and printing with movable type. In addition, during the same period, Europeans had

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[5] The original theoretical model on strategic information transmission is by Vincent Crawford and Joel Sobel (1982).

invented eyeglasses and the mechanical clock.[6] They had done so using Latin, a vehicular language that few were able to read. In England, for example, on the eve of the Reformation, the male literacy rate was probably between five and ten percent and the female rate even lower (Graff 1987/1991, 106).

The explanation, we will see, is that further progress was blocked by the inability of inventors and their assistants to develop a small number of key technologies that required the combination of complex concepts from widely differing areas of specialization. Linguists Gilles Fauconnier and Mark Turner (2002) have termed this process “double-scope blending”, the integration of two concepts whose structures conflict radically with each other. An extension of existing social networks by one or two orders of magnitude was necessary, this study will argue, to permit individuals spanning the range of necessary competences to combine their abilities successfully.

The book is divided into two parts. In the first part, we will study in detail the technological dilemmas of early modern Europe and the way these problems were solved between 1700 and 1850. We will examine case studies of a small number of technologies that were not only highly innovative but also created abundant spillovers for subsequent innovators. Combining the concept of macro-inventions, proposed by Joel Mokyr (1990) and the notion of General Purpose Technologies suggested by Timothy Bresnahan and Manuel Trajtenberg (1995), we will refer to these innovations as “Super-Technologies”. They represent about one in twelve important innovations developed during this period.

In the second part of the book, we will look more closely at social networks and at the reasoning behind the two Collective-Action Problems we have discussed. These problems, it will be remembered, are first, shirking in fulfilling one’s share of a joint task and second, the inability to coordinate profitable cooperative efforts. We will then use statistical tools to test whether the expansion of social networks helped solve these problems. Is there evidence that the standardization of the English and French languages contributed significantly to the jump in innovation rates during this period by facilitating cooperation between strangers? In other words, were expanding social networks the mothers of innovation ?

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[6] For a recent review of the relative contributions of Asian and European inventors during the medieval period see Duchesne (2011, pp. 165-181) .

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Ten years ago I spent a sabbatical leave with Ulrich Witt and his team of young researchers at the Max Planck Institute of Economics in Jena, Germany. The setting was quite conducive to deep thinking: a *Jugendstil* (Art nouveau) house with a bright, modern Bauhaus extension on a wooded site overlooking the valley of the Saale River in the heart of Thuringia. Being free, temporarily, from the constraints of North-American university routines, one could return to fundamental issues. Over and over in the discussions with my German colleagues as the year passed, the question arose: where do new ideas come from? Is it sufficient simply to set up institutions – legal codes and systems of justice to administer them – and then let the human brain do its mysterious work? Or can we count on freely-functioning markets to provide the incentive to innovate. Neither approach seemed completely satisfactory to me, but I quickly realized that an assessment of possible answers could only be found by empirical research. But with what data should one begin? Fortunately, the Max Planck library had access to documentation from all over the European Union and personnel who were most willing to help. It was the beginning of an odyssey that is still proceeding.

I would like to express my appreciation to Ulrich Witt for encouraging me to work on innovation, a subject that he himself has examined from the standpoint of Darwinian evolutionary theory. He and his Jena colleagues – particularly Christian Cordes and Guido Bünstorf – made valuable contributions to earlier versions of this research. I am also grateful to Ulrich Blum for an invitation to present my preliminary empirical results to the Institute for Economic Research of Halle. Comments by participants at sessions of the Canadian Economic Association and the European Public Choice Society were also helpful. At the Université de Montréal, Michael Huberman was an unfailing sounding board for discussing the latest research on the Industrial Revolution. Comments by my colleagues, Andriana Bellou, Rui Castro, Bariç Kaymak, Benoît Perron and William McCausland were also greatly appreciated.

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At Cambridge Scholars, Carol Koulikourdi, Amanda Millar, Emily Surrey and the rest of the team have been superbly efficient in transforming the manuscript into book form.

The following figure was reproduced with the kind permission of Springer Verlag:

> Fig. 5-3: Joerg Baten and Jan van Zanden. "Book Production and the Onset of Modern Economic Growth." *Journal of Economic Growth* 13(3) (2008), p. 220.

I also thank the Lebrecht Photo Library for the permission to use the cover picture, Eighteenth century French ladies fashion and hairstyles during the reign of Louis XV.

Finally, I am most grateful to Brigitte Daversin for her constant support.

INTRODUCTION

It is a cool spring morning, and a steady rain is falling. Although the leaves are beginning to bud on the trees, there is a lingering trace of Scottish winter in the air. You decide that rather than brave the rain to climb up to the Castle and its grounds, a warm, dry museum might be more appropriate. A short walk from your hotel brings you to the National Museum of Scotland, a beige stone monolith lying below Castle Rock in Edinburgh's Old Town. Once in the building's bright new atrium, you notice some intriguing machinery on one of the floors above you. You climb the stairs and begin to wander among the exhibits, which explore industrial change during the eighteenth and nineteenth centuries.

Suddenly, you hear a deep boom that shakes the building. Turning in the direction of the sound, you discover an enormous structure 30 feet (nine m.) in height that resembles a gallows built for a race of giants. Hanging from a horizontal beam, instead of a rope and body, is a metal rod attached to an enormous piston. The descent of the piston has just pulled down one end of the beam. On an accompanying panel you read that you are looking at one of the oldest surviving beam engines. Built in 1786 to the specifications of a Scot, James Watt, its original purpose was to pump water and to grind barley for a London brewery.

It was one day in the spring of 1765 that Watt, 29, conceived a way of greatly improving an earlier device that had used atmospheric pressure to push a piston within a metal chamber that had suddenly been cooled by a jet of water. Watt later recounted that the idea occurred to him while he was walking across the Glasgow Green.

> I was thinking upon the engine at the time and had gone as far as the Herd's house when the idea came into my mind that as steam was an elastic body it would rush into a vacuum, and if communication was made between the cylinder [of the piston] and an exhausted vessel, it would rush into it, and might be there condensed without cooling the cylinder (Marsden, 2002, pp. 58-59).

Watt had hit upon the idea of a separate condenser that would avoid the energy lost in the older machine from alternately heating and cooling the cylinder and piston.

For many students of history, James Watt's invention of the steam engine captures the essential characteristics of the Industrial Revolution. At last, humans were able to harness a source of power other than animals, water or wind by converting heat into mechanical energy. Eventually, the device and its descendants would be used in a wide variety of applications, from pumping water and spinning cotton to driving ships and trains – in effect powering the Industrial Revolution. Watt's death in 1819 would bring to an end this extraordinary period in world history. The Scottish nation is justifiably proud of his contribution.

The story just told is correct in its essentials. But three qualifications are necessary if we wish to use it to understand the nature of the Industrial Revolution. First, the relevant period began a generation before Watt's birth in 1736 and continued for a generation after his death. In other words, instead of the sixty-year reign of George III (r. 1760-1820) chosen by Arnold Toynbee (1887) for his *Lectures on the Industrial Revolution*, we will be looking at a full century and a half beginning in the year 1700. Our period is also over twice as long as the interval from 1760 to 1830 that Thomas Ashton (1948/1962) examined in his famous study, *The Industrial Revolution*.

The reason for starting our story so early is that the crucial breakthrough, it is now clear, was not Watt's separate condenser but rather the discovery a half century earlier of how to put steam to work. Indeed, the Industrial Revolution may be seen as a sequence of spillovers that began with the almost simultaneous invention of the atmospheric engine and casting with coal-smelted iron. . This remarkable discontinuity in world history may be seen as nearing its end almost a century and a half later, in 1845. In that year, an iron, propeller-driven steamship, the *Great Britain*, docked in the harbor of New York, fourteen days after leaving its home port of Bristol. Rapid technological change would henceforth be a constant feature of the human condition. Between these two bookends, Watt's contributions were very clever spillovers from the work of his less well-known predecessors.

A second correction is that Watt's insight of 1765 marked not the end of his difficulties but the beginning. To develop his idea, he would require not only time and money, but also technical expertise in the manufacture of precision machinery. Consequently, the development of this invention depended not only on Watt's genius but also on the *willingness to cooperate* of others. As Michael Polanyi (1944, p. 71) wrote in discussing patent reform, "invention … is a drama enacted on a crowded stage".

You may have noted in the Edinburgh museum that the inscription on the name plate of the thundering beam engine was not Watt but *Boulton and Watt*. Fortunately, Watt himself was an instrument maker. Eight years previously, he had begun to borrow money from the Glasgow merchant John Craig to finance an expansion of his shop. However, in December 1765, the year of the discovery just described, Craig died, and his trustees demanded the return of the amount owed, some £757. Watt had also borrowed £150 from his friend, Joseph Black, a Glasgow College chemistry professor.

Black advised Watt to consult one of his former students, John Roebuck. The English industrialist was trying to find an economical means of pumping water from his coal mines at Kinneil, situated half-way between Glasgow and Edinburgh (Marsden, 2002, p. 71). Roebuck, who had earlier developed an industrial process for producing lead, agreed to repay Watt's debts and help finance the building of a working model of Watt's proposed engine. In return, Watt would have to cede to Roebuck two-thirds of the eventual profits from the machine. In 1768, after building a small model engine, Watt traveled to London at Roebuck's bequest to apply for a patent for the following invention: "A method of lessening the consumption of steam in steam engines – the separate condenser". The patent was granted in January 1769. However, Watt had no sooner built a "working scale" engine than he learned that his patron was on the verge of bankruptcy and had sold the patent to an English manufacturer named Matthew Boulton whom Watt had met previously (Marsden, 2002, p. 82). Yet the development of the engine was by no means complete. Watt realized that he needed a more precisely-bored cylinder and a more robust piston before his machine could compete successfully with existing techniques for draining mines. How could he convince Boulton and his English associates to cooperate with him?

There is one final qualification to the story of James Watt's invention of the steam engine. As we will see in Chapter 3, James Watt is associated with more important contributions to the Industrial Revolution than any other inventor. However, only one of these inventions occurred in Scotland. The others were developed in the English Midlands, in the rapidly-growing town of Birmingham where Matthew Boulton lived. An essential part of the present study will be to examine why the West Midlands, along with a few other small regions in England, France and the United States, accounted for well over half of all of the important innovations in the world over a period of 150 years. How can this extreme spatial concentration of innovation over such a long interval be explained?

Mater artium necessitas?

There is a saying sometimes attributed to Plato that necessity is the mother of invention. There have undoubtedly been cases over the past two millennia where desperation has led people to look for new ideas. But if one talks of *innovation* in the sense used by Joseph Schumpeter (1934/1983, p. 133)in *The Theory of Economic Development*, that is, the successful application of a new idea that enables a unit of product to be produced at a lower cost, then necessity does not seem to have played a large role in Watt's discoveries. Britain's coal mines and textile mills would have survived quite well with the existing technologies of animal- and water-power as Nick von Tunzelmann (1978, p. 4) has demonstrated. Watt himself had a successful business as an instrument maker and engineering consultant. The key factors behind his initial interest in the steam engine seem to have been intellectual curiosity and the moral challenge of avoiding the waste of energy that he had discovered while repairing a model of the Newcomen atmospheric steam engine for Glasgow College (Marsden, 2002, p. 50). Even so, in 1770, despite an interesting original idea and five years of work, Watt did not as yet have a practical device that he could sell to mine owners for pumping water from their underground seams. His invention was still far from becoming a successful innovation.

What, then, is the source of innovation [no pun intended]? The question is one of the most important issues in economics, since it is innovation that drives technical progress. Technological change in turn is the main component of long-run productivity growth. From Arnold Toynbee in the 1880s to Thomas Ashton in 1948, economic historians were generally content to *describe* the inventions that had changed the face of Britain while speculating on the reasons for that country's economic rise. However, more recently, attention has focused on *explaining* the process of innovation itself. This challenge became especially important after 1957, when Robert Solow demonstrated that total economic growth could be broken up into two components. The first component is the part attributable to the growth in stocks of factors of production such as labor and capital. The second, and more important, is the part due to increases in the productivity of these factors (Solow, 1957).

Nicholas Crafts and Knick Harley have estimated that growth in total factor productivity explains over two-thirds of the rise in per-capita income that occurred in Britain between 1760 and 1830 (Crafts and Harley, 1992, 766). As recent books by Joel Mokyr and Robert Allen have made clear, there are two competing approaches to explaining the technical change that yielded this productivity growth – the Industrial Revolution. On the one hand, Mokyr has argued that institutions and ideology together determine the *supply* of innovation. On the other hand, Allen has emphasized that changes in relative factor prices establish the incentives to innovate on the *demand* side.

In his book, *The Enlightened Economy*, Joel Mokyr (2009, pp. 30-37, 66-67) used the supply-side approach to explain Britain's lead in industrial development between 1700 and 1850. 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 Douglass North and Barry Weingast (1989) 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. Moreover, throughout the eighteenth century, Mokyr (2002, pp. 63-65) argued, the British Enlightenment with its emphasis on "useful knowledge" encouraged the application of mathematics and science to satisfy social needs.

One may readily agree that the institutional and ideological considerations identified by North and Mokyr did favor innovation in Great Britain. However, they seem not to have been the whole story. If we wish to use a single cause to explain international differences in innovative performance, we must be wary of possible counter-examples. On the one hand, there is the false positive of the Netherlands, which like Britain was governed by a set of representative institutions that spread decision-making power among elected representatives, although as a federation of seven provinces rather than as a unitary state (Israel, 1995, p. 246). Individual rights to freedom of movement and contract were better protected there than anywhere else on the Continent (de Vries and van der Woude, 1997, pp. 161-162). However, the Netherlands contributed very little to the wave of innovation after 1700. On the other hand, there is the false negative of France, which since the beginning of the personal reign of Louis XIV in 1621 had been governed as an absolute monarchy with little protection for the rights of the individual. In times of war, the state would raise needed revenues by selling new official positions and privileges – a process known as venality – or extort funds by threatening existing offices (Swann, 2001, p. 152). Yet the French were the first to apply science to the industrial production of chemicals. And French inventors were also the first to develop techniques for controlling production through information coded in binary fashion.

In a second study, *The British Industrial Revolution in Global Perspective*, Robert Allen (2009) presented the 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 increasingly expensive traditional energy sources, he argued, provided an incentive to devise production processes that made intensive use of cheap capital and coal. Initially, a crucial question in the development of an innovation was the size of the local market for new techniques. Subsequently, along each path of invention, learning from experience led to a series of adaptations that improved the productivity of the original breakthrough. These later steps were relatively insensitive to factor prices (Allen, 2009, pp. 151-155).

Once again, however, the evidence presented is not sufficient to explain either the location or the timing of the key British innovations. Before 1775, real wage rates were even higher in Amsterdam than in London (Allen, 2009, p. 40). And coal from Newcastle was no more expensive in the Netherlands than in southern England (de Vries and van der Woude, 1997, p. 719). Moreover, as Nicholas Crafts has argued, the invention of the spinning jenny would also have been profitable in France. As for the timing, Crafts pointed out, Allen's own data would support development of the jenny in England a century before James Hargreaves invented it (N. Crafts, 2010, pp. 158-159).

The approaches of Mokyr and Allen are more complementary than competing, both helping to explain Britain's role in early industrialization. Yet there seems to be something missing from the combined story that they tell. In particular, they have difficulty explaining why rapid innovation began in multiple regions of Britain, France and America during the eighteenth century but not in Belgium, the Netherlands, Germany or Italy – or indeed anywhere else on the planet. As historian Ricardo Duchesne concluded after reviewing the recent literature on the relative stagnation of technology in China and the Islamic world compared to Europe after 1500:

> *The conduct of British machinists and entrepreneurs in the eighteenth century were not mere responses to institutional incentives. They were authentic values infused with a religious zeal and a spirit of conviction* (Duchesne, 2011, p. 202).

If institutions and prices alone are not able to explain the timing and location of innovation during the Industrial Revolution, what is the missing factor that might have triggered this burst of accelerated innovation? Interest in this question is not limited to those who specialize in eighteenth-century British economic history. As Dierdre McCloskey asserted while surveying research on British economic growth in the period from 1780 to 1860, the challenge is to explain why real income per head in Britain today exceeds that of the eighteenth century by a factor of twelve (McCloskey, 1994, p. 242). The same ratio, or something very similar, she pointed out, applies to other countries that have experienced modern economic growth. This improvement in living standards greatly exceeds that of any other episode in world history. At the heart of the issue, she concluded, is the nature of innovation itself. "Between the conception and the creation, between the invention and the innovation, falls the shadow" (op. cit., p. 269).

In a recent book, Steven Johnson proposed an approach that promises to shed light on McCloskey's "shadow". Applying an analogy from physics, he contrasted three states of matter: solid, gas, and liquid.[1] In a solid, the structure is stable but resistant to change. In a gas, in contrast, although random interactions are much more probable, any new structures are likely to be destroyed instantly. Between the two is an intermediate state – a "liquid network" – that permits change but is stable enough that new combinations last for some time (Johnson, 2010, p. 52).

Humans are of course very different from randomly interacting molecules. They have the ability to reason and can therefore calculate expected gains and losses before deciding whether to interact with one another or not. Moreover, since humans have memories, they can take into account the consequences of previous interactions when they make their decisions. Finally, humans can communicate with one another, transmitting signals that others can use in their own decision-making. Nevertheless, we should keep Johnson's three-state analogy in mind while searching for the sources of innovation. Let us consider, then, a possible example of a "liquid" network.

In the case of the steam engine with separate condenser, it is helpful go back to a moment two decades prior to James Watt's journey from Glasgow south to Birmingham. In the year 1744, Matthew Boulton, age 16, was about to graduate from the academy of the Reverend John Hausted in Deritend, Birmingham and join his father's buckle factory (Tann, 2007). Meanwhile, 300 miles (500 km) to the north, James Watt, eight years younger, was learning his ABCs at M'Adam's school in Greenock near Glasgow (Tann, 2007). At age eighteen, he would go on to begin an apprenticeship with an instrument maker. Neither Boulton nor Watt would

[1] Johnson (2010, p. 52) credits computer scientist Christopher Langton with applying the metaphor of different phases of matter to the process of innovation.

ever attend an institution of higher education. Yet despite growing up on opposite sides of the English-Scottish border, they could speak and write the same language. They would meet by chance through a mutual acquaintance in 1768, each immediately realizing the possibilities of a potential collaboration (Marsden, 2002, p. 76). However, it would take the financial difficulties of Watt's initial partner, Roebuck, to make their association possible.

If Boulton and Watt had grown up in German or Italian towns equally distant, it is unlikely that they could have communicated so easily. In these nations, in the mid-eighteenth century, each region had its own dialect. France was an intermediate case. It would take almost another century before France as a whole attained the literacy rate that England had reached in 1750 (Graff, 1991, pp. 195, 232). Moreover, France in the eighteenth century was linguistically less homogeneous than Britain. The farther from Paris individuals were born, the lower was the probability that they spoke Standard French. The southern third of the country's population conversed in Occitan, while around the periphery, people spoke Breton, Basque, Catalan, Italian, German or Flemish. Nevertheless, by 1793, the Abbé Grégoire calculated, of France's 28 million people, over half were able to converse in the French language (Gildea, 2002, p. 164). Yet because France's population was almost three times that of Britain, the French-language social network was comparable in size to that of the English-language network across the Channel (see Table 5-1 below). For Germans, however, the emergence of standardized linguistic norms would not come until the second half of the nineteenth century (Hawkins, 1990, pp. 114-115). Italians would have to wait even longer.

We see, then, that if Johnson is correct, the degree to which the social networks of Western Europe were "liquid" may help to explain observed differences in innovation rates between Britain and France on the one hand and the rest of Europe on the other. But why might the British and French social networks have attained the right consistency first? Might the explanation have something to do with the capacity of people to communicate with one another?

A Starting Point

A good moment to begin our inquiry is a century before the beginning of the Industrial Revolution, on the morning of Saturday 14 January of the