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The spark that ignited the Industrial Revolution

An examination of the institutions surrounding the development of the steam engine in England and France

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Preface and Acknowledgements

A burst of steam is released into the air, as a mist of an idea. If you can solve the mystery of how to capture that breath of steam (or idea), you can turn it into power. – Joshua Bragg

My first encounter with steam power was as a child, anxious for a mug of hot chocolate after coming home from school one rainy day. I needed to mix hot water with the cocoa powder, so I filled our teakettle and put it on the stove with the highest heat possible. My attention span lasted about thirty seconds before I left the kitchen and turned on the TV to watch a G.I. Joe cartoon. Finally, when a commercial came, I remembered my task at hand. Returning to the kitchen, I saw that the lid to the kettle was jumping up and down as if it was ready to explode. As I reached to turn off the heat, I burnt my arm from the steam rushing out from the loose lid, searing the memory into my mind for use thirty year later.

There is a similar story told of one of the fathers of the Industrial Revolution, James Watt, who as a twelve-year-old boy was scolded by his aunt for staring at the kettle for hours. The difference though is stark. Although we both were inspired by the power of steam raising the lid of a kettle, only James Watt went on to build a steam engine. In contrast, I chose to write about it. The topic was motivated by a desire to understand economic growth and what made the West rich. With that came a realization that technological innovation actually generates most growth. This is especially apparent when investigating the impact of the steam engine, which ended up powering a large part of the Industrial Revolution. Applied to transportation, the steam engine locomotive and ship connected the world, allowing for a tightly integrated global economy. With a huge increase in energy, that was no longer dependent on wind, water or muscle power, the factories and machines that manufactured our wealth multiplied.

Writing this thesis has been one of the most enjoyable endeavors of my life. As I have struggled to balance a challenging career in the insurance industry with the demands of family life, I found myself looking forward to the peaceful moments when I could spend countless hours studying. I savored every moment reading the over one hundred books and articles that sparked the ideas written here. The reason this project has actually been enjoyable is that it is a subject that brings together all the fascinating parts of science, economics, politics and especially history, combined with a boatload of enthralling characters.

My first debt is to the marvelous economic historians, with whom I've spent most of my free time with during the past year, including my favorite Joel Mokyr, the unconventional Deirdre McCloskey, the very convincing Robert Allen, the non-conformist Nicholas Crafts, the brilliant Margaret Jacob, the provocative Gregory Clark, the Francophile Jeff Horn, and the steam engine expert Alessandro Nuvolari. They also comprise the recently departed, who live on in the knowledge they shared, like the pioneer Douglass North, the genius on technological change Nathan Rosenberg, the "culture" champion David Landes and the great French francophobe anglophile François Crouzet.

A number of professors at the Norwegian University of Life Sciences Business School bestowed their stimulating instruction that encouraged me to investigate many various facets of economics. My econometrics teachers Olvar Bergland and Kyrre Rickertsen ironically instilled

in me both an appreciation and a critical eye towards the field. Roberto Garcia imparted the power of international comparisons, which was adopted in this paper. Arild Angelsen provided considerable practical advice and encouraged my unorthodox approach to this master’s thesis. Rani Lill Anjum pushed my boundaries by demonstrating how philosophy can enlighten even economic discussions of causation. Rani and her eternal PhD student Fredrik Andersen were a constant source of moral support and humor throughout my studies. Many of the most interesting discussions at the university were sparked by the delightful Mette Wik, to whom I am especially grateful for her serendipitous introduction to Sigurd Rysstad. Sigurd has proven to be the perfect advisor for this Master’s thesis. He has gently prodded me towards fascinating new research that has greatly enhanced my ideas on institutions, path dependence and the theories of innovation. I have benefitted immensely from his invaluable advice on the structure and readability of the paper.

I also received critical support and mathematics tutoring from fellow NMBU student Nguyen Nhung Lu and Daumantas Bloznelis. They are both extremely gifted individuals and I bask in our friendship full of discussions on economics and life. More gratitude goes to my former professor of economic history at the University of Copenhagen, Karl Gunnar Persson, who started me down this course and continues to provide encouragement, even in retirement. There is also the indispensable mentor who first gave me the “economics bug” and got my twenty-one year old mind to start thinking critically – James Craven, my instructor at Clark College in Vancouver. My life is rich with thoughts and ideas because of his unorthodox teaching.

Special thanks goes to my wife Katherine and daughter Josephine, who put up with an international move, piles of books and papers, countless hours of “quiet” weekend study time and a sometimes stressed husband and father, all for this thesis. I promise it can only get better now.

This thesis is dedicated to my parents, from whom I have inherited a love of books, history and learning. My mother is the only non-economist (her Master’s degree is in sociology) who follows my thinking, often providing wonderful insights of her own. She has proofread all my school papers from the first grade on and this one is no exception. Her prodigious editorial talents and capabilities embody good economical writing. I am eternally grateful for the intellectual imprint she has left on me. Finally, I owe a great debt to my father, who shared with me an unforgettable summer day in 2014 at the Musée des Arts et Métiers in Paris, where I discovered numerous French contributions to technology, including the amazing steam powered vehicle from 1770. I will forever treasure the memories of writing this thesis in his office and at his side, both of us “working hard and getting things done”. I am sending the muse back to him as he writes his wonderful life’s memoirs.

Introduction

> *"If economics, applied to history, is to have any claim to validity and relevance, it should above all else be able to explain what is arguably the greatest event in economic history" – Peter Jay (2000)*

We arguably live in the best time to be alive since the beginning of humankind. This is a world in which my standard of living would be unthinkable to my great grandparents and even today's poor are incredibly rich and literate by historical standards. My family lives with minimal fear for our safety and we are in charge of our own politics. Also unthinkable just a few generations back, I was educated well into my 20s and have the luxury of continuing into my 30s as well as my parents who have the potential to live in retirement for 30 to 40 years past their working careers. Compared to my ancestor, Joseph Bragg, a free white man living in the British colony of Virginia in the early eighteenth century, I am better off economically by a factor of over twenty[1]. While Joseph was presumably better off than his grandfather, Thomas, who was one of the first settlers in Jamestown in the early seventeenth century, the improvement was largely due to the colony getting its feet on the ground as well as the lucrative tobacco trade. In other words, the livelihood of my early American ancestors was dependent on precarious and fragile factors, such as the weather, trade and support from England and peace with the native inhabitants.

What changed to cause the economic transformation, which slowly started increasing real income in the eighteenth century in Northwestern Europe and took off in the Western world in the nineteenth and twentieth century? Commonly known as the Industrial Revolution, many economic historians have correctly classified what happened as an inventive revolution. Invention was not new, as we can trace advancements in tools, sea travel, agriculture and warfare from the Paleolithic era to medieval times. However, these creative bursts merely allowed one civilization to conquer another or expanded their population or geography. While these technological advancements brought more people into the world, human existence was best described by Thomas Hobbes (1651/2003, p. 89) as "solitary, poor, nasty, brutish, and short." The key to breaking this curse was simply a change in the way of thinking about invention. This paradigm shift ended up transforming the world more than any religious or political revolution could dream of, merely by generating a sustained flood of new technologies.

The Industrial Revolution did not occur out of the blue or randomly in Western Europe. Just as John the Baptist set the stage for Jesus Christ, it was preceded by a process coined "the Great Divergence". If we think of the world being in a race for wealth and power, in 1500, Europe was relatively on par with civilizations in China (where gunpowder, the compass and the printing press were first invented), Japan, India and the Ottoman Empire. Then, as illustrated in Figure 1 using the Maddison Project's GDP per person statistics, Western Europe gradually began to surpass the competing world powers.

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[1] If my ancestor was by chance American Indian or Black, any comparison would be a cruel reminder of the racial inequities in American society.

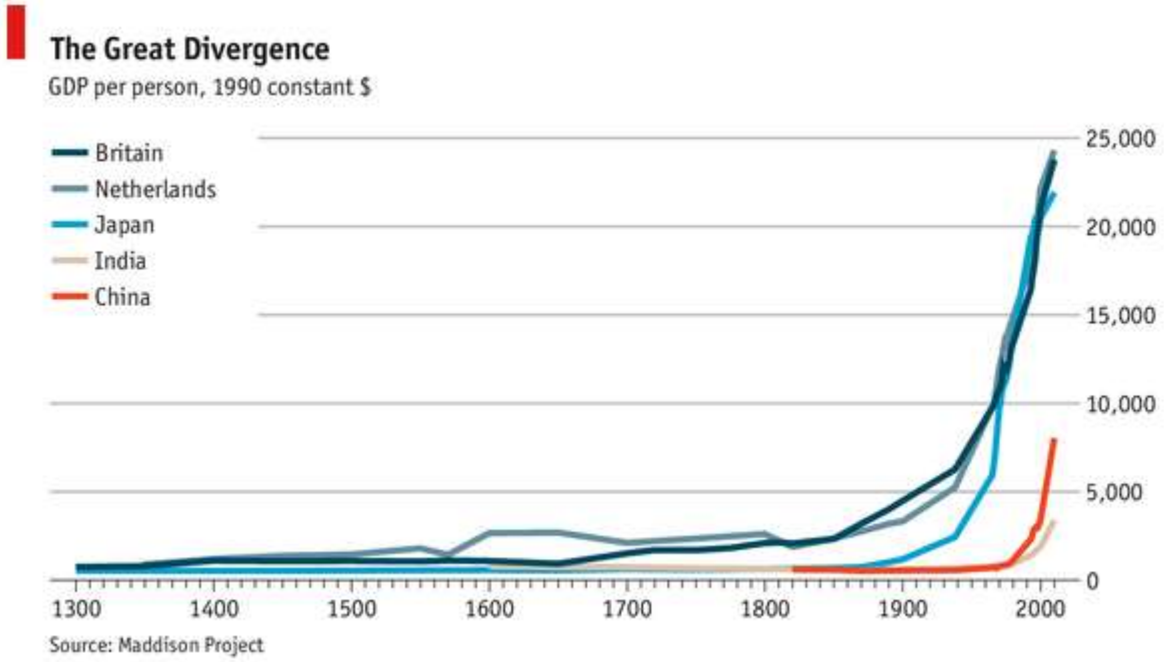

Figure 1 - What was the Great Divergence? (Economist 2013)

The Age of Discovery (15th to the 18th century) led by Christopher Columbus, first gave the European powers a head start, as they began extensive overseas exploration. They soon established colonial empires, which conquered, exploited and enslaved native populations in the Americas, Asia and Africa. The Commercial Revolution (16th to the 18th century) exemplified by the Dutch East India Company, also contributed to European expansion by building vast international trade networks. Meanwhile, back in Europe, a scientific renaissance recovered the knowledge of the ancient Greeks and medieval Islamic science. However, those ancient ideas were merely a foundation for the subsequent Scientific Revolution (16th and 17th centuries) that created new, revolutionary concepts in understanding the physical world. The next European impetus was the Enlightenment (18th century), in which the authority of the church and state could be questioned and ideas centered on reason, such as liberty, progress and constitutional government, gained legitimacy. By the 18th century, China, Japan, India and the Ottoman Empire had all but dropped out, while the race centered between the Western European powers.

These milestones led up to tremendous advances in useful knowledge, culminating in the Industrial Revolution which began in one single country, Britain. This was an event that dramatically and irreversibly transformed Britain, and later the rest of Western Europe. It forever altered both the economy and culture, including changes in the methods of production and work and the way economic transactions in society took place, leading to better living standards for the whole population. It was eloquently summarized by Harold Perkin (1969, p. 3-5) as:

> *a revolution in men's access to the means of life, in control of their ecological environment, in their capacity to escape from the tyranny and niggardliness of nature…it opened the road for men to complete mastery of their physical environment, without the inescapable need to exploit each other.*

The Industrial Revolution differed from the previous milestones in European history as it ushered in an era in which technological change and economic growth overpowered population growth. Previous bouts of growth were sporadic and fleeting due to institutional breakdowns, wars or natural disasters. However, the Industrial Revolution was not merely built on a fleeting expansion of commerce or peaceful political circumstances. Rather, its foundation was technology, which is much less reversible and allowed the economy to shake off the chains that had shackled it until the mid-eighteenth century. That single event has created a sophisticated and urban population that is wealthy beyond anyone's wildest dreams two-hundred and fifty years ago.

Research Questions

Given its tremendous consequences, the Industrial Revolution begs the questions: *Why there and why then?* If the engine of industry was primed in the countries of Northwestern Europe, given their relatively similar starting points, why was the spark first lit in Britain[2]? Only France stood out as the most realistic competitor. Both Britain and France possessed the intellectual and social infrastructure necessary for modern growth.

England and France are more like siblings when compared to the distant cousins of China or the Ottoman Empire. They loosely share a similar DNA stemming from a common Norman heritage after the Battle of Hastings in 1066, but a closer look reveals significant "genetic" differences shaped by the "Hundred Years' War" and frequent petty squabbles and competition leading to distinct historical experiences of Britain and the Ancien Régime of France. While they once shared the same language, religion and monarchy, by the eighteenth century the siblings had grown apart, creating distinct political, social and economic institutions. However, a quick examination of the scorecard between the two nations in the mid-eighteenth century shows similar levels of property rights. Britain protecting hers through its parliament and patent system and France through its strong central government and highly organized judiciary. The scientific enlightenment reached both countries, through their respective prophets Francis Bacon and Rene Descartes. On the record of technological innovation, both countries proved extremely impressive for the time.

It has been argued that Britain's lead was merely the result of a random or stochastic process of technological progress, where arguments of French inferiority and unique British factors are merely post hoc ergo propter hoc fallacies. While this may or may not be the case, it spurs a valuable shift in thinking about the spark. Rather than asking "what made France inferior?" the question shifts to whether there were factors present in eighteenth century England which gave it a higher probability to spark the Industrial Revolution. So, no longer presuming that the probability was higher in England just because it was first, one could also ask whether there were factors that made the probability of the Industrial Revolution high in eighteenth century France.

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[2] My American education taught that it was Britain who unequivocally lead the race from 1815 to 1918, when it reluctantly handed the title to its little brother, the United States. This Anglo-Saxon perspective glosses over the miraculous development elsewhere in Western Europe and the world, such as Germany and Japan's rapid industrialization.

The great economic historian Joel Mokyr (1985, p. 83-84) provided an apt warning to those who might attempt such an inquiry:

> *Examining British economic history in the period 1760-1830 is a bit like studying the history of Jewish dissenters between 50 B.C. and A.D. 50. At first provincial, localized, even bizarre, it was destined to change the life of every woman and man in the West beyond recognition and to affect deeply the lives of others.*

Why did England dominate steam engine development and not France?

However, if the Industrial Revolution was a technological revolution, valuable insights can be gleaned from an intensive investigation and analysis into a case study of an invention. Answering why the spark was first lit in Britain and not France can be richly illustrated using the case study of the invention and development of the steam engine. There are numerous inventions cited as the mother of the revolution, however, despite its slow and modest start, the steam engine was crucial to the industrialization of modern civilization.

The steam engine was born as a powerful mining pump that kept Britain supplied with cheap coal, which fostered numerous synergies, including iron and steel technologies, that would in turn build better engines. A floodgate of innovation was released in factories as the engine was adapted to power industrial activity. By the turn of the nineteenth century, it generated a leap across an energy canyon[3], drastically surpassing the age-old limits imposed by wind, water and muscle power. The abundance of mechanical energy made dreams of efficient transport a reality, as the engine was applied to ships and locomotives, providing access to goods and services to most of the population. Since the steam engine was arguably the power source that drove the industrialization of Britain, it provides the best case from which to make generalizations about the sources of British primacy.

A comparison of the invention between Britain and France is especially thought-provoking since the countries appeared on quite equal footing in scientific knowledge, market size, and colonial powers at the onset of the eighteenth century. Economic historians have countless theories that would seem to explain why the invention and development of the steam engine occurred in Britain. This paper does not subscribe to a single theory, but utilizes several hypotheses in order to identify viable factors believed to cause or increase the probability of the steam engine to be invented and enhanced in Britain. It also contrasts those factors with the French experience in order to ascertain the probability that it could have first occurred in France.

Journey into Great Economic Mysteries

It is already apparent that the presentation of this thesis differs from most others in the field of economics. While it opens with a clear and fascinating research question, a hypothesis is not initially stated. This is intentional in order to distance this research from a theoretical form

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[3] Energy canyons are the inevitable limits placed on life and humanity at certain milestones of a seemingly unsurpassable boundary of energy, requiring an external jolt to push past the frontier and onto the other side of the canyon.

of economics that does not reflect historical events. Rather than top-down deductive logic that assumes abstract theories to be true, this paper employs inductive reasoning by studying the working of the actual economic systems. Taking inspiration from the great detective character Sherlock Holmes, this thesis will gather all the facts available in order to extrapolate a conclusion about causal factors. Just like any mystery author knows, you do not reveal "whodunit" until the very end.

Before answering the exciting question of why England and not France invented the steam engine, this thesis will embark on a journey through the typical sections that exemplify good research. First, relevant *background* into the understanding of economic growth, including the importance of innovation and human capital accumulation as well as their interdependence. However, as economic theory alone is unable to explain the cause of the Industrial Revolution, it becomes apparent that institutions hold the key to the mystery of economic growth. Stepping outside the narrow constraints of economics allows a deeper understanding of what causes invention.

After relevant background information is provided, the *terms* and *theories* surrounding innovation are reviewed and integrated, concluding with a probabilistic approach rather than a "one-size fits all" attitude. The theory section is also enhanced with a comprehensive *literature review* comprised of attempts to answer the comparable "Why England?" puzzle. These theories provide the basis (or set of hypotheses) of potential explanatory factors that will be examined in the context of the steam engine's invention. Then, the *methods* for analyzing the data and a justification of the chosen methodology are presented. Prior to an examination of the results, the paper offers additional background into the invention of the steam engine and its workings. With the stage now set, the comparative analysis of the factors surrounding the invention is reported in a clear and structured manner. The *results* are finally *discussed* and *interpreted* for their probability in causing or contributing to the invention, before the guilty (or causal) factor(s) are revealed.

Background

Energy Canyons

In the spirit of *big history*, I will begin at the beginning – the origins of life, which suddenly occurred after billions of years in the midst of an ocean of lifeless chemicals. Somehow, these elements produced a pulse, but again for two billion years, life on earth of stayed content as miniscule and simple single-celled organisms, with no significant change to their basic form. Then, suddenly these microorganisms made a radical transformation to complex life. We now take it for granted that there is a multitude of life in our oceans, forests, cities and skies, but there is no rule that biological life will get bigger and more complex. The great and vital question of biology and our very existence – "how did life begin?" - remains a black hole. Biochemist Nick Lane (2015) provides one intriguing theory that explains how simple cells overcame the barrier that prevented growth and new forms of life. Complex modern life, with its DNA and many moving parts, requires a lot of energy. Somehow, one of those primitive single celled organisms was jolted with a force[4] that powered it to the other side of an energy canyon. This generated a new large and complex type of life as we see today in jellyfish, orangutans, cherry trees, tarantulas, and college professors.

Another evolutionary theory dealing with energy explains how the homo genus differentiated itself from all others. When our ancestors adapted to using fire to cook its food, the energy previously spent on chewing and digesting tough raw food could be used to hunt, forage and explore. As the digestive tract shrank, the brain grew, propelling humans over another energy canyon (Wrangham 2009).

The next hurdle to face humanity was economic and took over one hundred thousand years to overcome. Life, in terms of food, clothing, heat, light, shelter and life expectancy, did not get better from one generation to the next. The Reverend Thomas Robert Malthus (1798/1986, p. 61) made the critical insight that any short-term improvements to income from a technological advance were inevitably eaten up by population growth.

The Sources of Economic Growth

The most significant question economists have spent over two hundred years attempting to answer is how some nations escaped the Malthusian Trap, drastically improving material conditions from one generation to the next. The reason for this topic's importance is precisely because it is also the primary objective of the world's governments. Most countries view economic growth as a necessity to raise the income, well-being and the potentials of their people and thus it is the most crucial social task facing the world today. If one contemplates the variations in growth in the world since 1700, it is clear that some regions, such as North America, Europe and Australasia have achieved tremendous prosperity, while other nations in Africa, South America and Asia struggle to survive.

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[4] Mitochondria today contain an amazingly strong electrical charge, one-hundred and fifty million millivolts, which for their size would be the equivalent to a bolt of lightning.

Robert Lucas (1988, p. 5) eloquently elaborated this point in his Marshall Lectures on economic growth:

> *I do not see how one can look at figures like these without seeing them as representing possibilities. Is there some action a government of India could take that would lead the Indian economy to grow like Indonesia's or Egypt's? If so, what, exactly? If not, what is it about the "nature of India" that makes it so? The consequences for human welfare involved in questions like these are simply staggering: Once one starts to think about them, it is hard to think about anything else.*

The attempt to identify the key variables or fundamental causes of economic growth occupies economists because of the extraordinary impact such a discovery would have on the world. The Industrial Revolution, with its inherent economic growth, transformed parts of Western Europe and North America to a society where each successive generation's purchasing power is greater than the previous and where most individuals have the economic means to reach their potential. It is arguably the most significant event in human history, but its cause is not yet scientifically explained. Finding the cause or precise recipe to sustained economic growth is the holy grail of economics. If there is one universal cause or set of causes, it could be replicated throughout the developing world and truly eliminate poverty.

The grandfathers of economics, Adam Smith, David Ricardo, Thomas Malthus and Karl Marx provided the first basic answers to why economies grow by breaking the growth process down into three building blocks, namely, land, labor and capital. These categories were easy to understand as they refer to everyday things found in the economy. Land signifies the productive capacities of the earth itself. Labor is the diverse effect and talent of workers. Capital is the equipment used by those workers as well as the financial assets throughout the economy. Economic theory was largely based on these components, such that they were used to argue about who should produce what goods and for whom and which responsibilities properly belonged to the state versus those which were best left to markets.

In the classical theory of economic growth, best exemplified by the Harrod-Domar model, technological progress is dependent on capital (both its accumulation and its productivity), so the fundamental cause of innovation was savings and investment (Solow 2000, p. 52). It is ironic that the most important parameter in the Harrod-Domar model, the savings rate, is exogenous (its result is not determined by the model). One could argue that savings itself is dependent on the profit expectations of entrepreneurs. Like any well-educated toddler, you should continue asking "why" until you find the root explanation. In this case, when you ask a classical economist what determines the profit expectations, the answer ironically would be technological progress. This circular argument, that nothing succeeds like success and nothing fails like failure, is still prevalent today, but does not get us any closer to the fundamental causes of economic growth.

The Mystery of Economic Growth

The field experienced a resurgence in the 1950s when Robert Solow developed a model that added a residual factor the original sources of growth. The unexplained residual was a catchall variable for technological progress or any other changes that affected the productivity of inputs, such as technological change and increasing skills among workers, and later became known as Total Factor Productivity (Solow 2000, p. xxi). Using growth accounting, Solow decomposed the growth of output into the sum of their inputs, which found that the residual is the largest contributor to economic growth. In fact, Solow's (1957, p. 320) study concluded that about seven-eighths of the increase in output per head in the American economy was traceable to such productivity increases. Nevertheless, within the theory, the residual was treated as a question, not an answer. It is used to explain the observation of economic growth, but could not be used to predict it.

I still vividly remember the lecture over fifteen years ago when I first learned about the unsolved mystery of Solow's Total Factor Productivity, in a gorgeous Neo-Classical style classroom dating from 1728 at the University of Copenhagen.

Figure 2 - University of Copenhagen's Metropolitan School building (first built in 1209) in Vor Frue Plads (literally "Square of Our Lady")

While the surroundings provided a stunning backdrop, it was the idea that something so fundamental to our way of living, could be measured, but not yet conclusively explained (like dark matter). Economists knew that there were other factors involved in the economy, but these were treated as exogenous, which means that they are not part of the theoretical models created. Exogenous factors are to an economist what material that will not be included on the course exam is to the student.

The course's next lecture described the great advances in refining Solow's original model to include (or endogenize) the role of innovation, knowledge, increasing returns (Romer, 1986) and human capital accumulation (Lucas, 1988) into a growth model that would explain the sources of the residual. The search to explain these less tangible and previously mysterious factors brought to light a myriad of insights regarding the creation and impact of human capital. Theodore Schultz pioneered this research[5] (and deservedly won a Nobel Prize) with his observation that people's skills and knowledge are capital and are subject to the same investment decisions (rate of return) as conventional physical capital. He also showed how investment in human capital, such as spending on education and health, have led to "most of the impressive rise in the real earnings per worker" (Schultz 1961, p. 1).

Gary Becker expertly took the torch from Schultz, his University of Chicago School of Economics boss, in describing how the application of scientific knowledge through education and on-the-job training with a healthy work force leads to a virtuous cycle of economic growth (Becker 1993, p. 24). The field has had a tremendous impact on governments around the world who have incorporated education subsidies and job training programs in their struggle to deal with labor displacements due to economic globalization.

Endogenous Growth Theory: One Step Forward, Two Steps Back

The fact that knowledge and technological process are key components of economic growth seems so common sense today, but it was not until 1990 when a thirty-six year-old economist named Paul Romer (1990) published a revolutionary paper with the simple title "Endogenous Technological Change", that the role of knowledge took center stage in explaining economic growth. Endogenous growth theory should be applauded for taking a great leap towards incorporating all relevant variables into a theory of economic growth, not only by endogenizing technology creation, but also going a step further by positing what fundamentally drives technological change. This brilliant addition to economic theory provided very applicable real-world conclusions. For example, building on the ideas of Schultz and Becker, Romer highlighted the importance of human capital in generating growth and the use of trade to stimulate the accumulation of human capital.

New economic growth theory has provided answers to the most pressing questions in the field, yet the theory struggles with empirical proof. Many economic historians (Crafts 1995; Voth 2003) have partly rejected the new growth models as their predictions do not square with the historical events surrounding the Industrial Revolution in Britain and France. While we now have a better and larger menu to choose from, many of the items are still indigestible.

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[5] Schultz's research into human capital was spurred by the question of why post-World War II Germany and Japan were able to rebuild and grow much faster than the United Kingdom, concluding that their healthy and highly educated populations contributed to their rapid recovery.

Another glaring issue with the theory is its failure to explain income divergence among world's economies. If countries have access to the same stock of knowledge, one would expect much more convergence to have taken place. Numerous studies have attempted to explain the difference in performance, citing various reasons why countries do not make efficient use of this knowledge. These share a common theme that economic institutions, cultural context, path dependence and history need to be included into analyses of cross-country income differences.

What Causes Invention?

While Endogenous Growth theory incorporates many of the factors which are strongly correlated with growth, such as investment in human capital or technological advances, it fails to identify how those factors come about. For seekers of fundamental causes, the theory only offers a weak explanation of technology (knowledge) creation. Specifically, David Romer (2012, p. 118) posits, "many innovations…are motivated almost entirely by the desire for private gain". Unfortunately, this account gives my inner-toddler a temper tantrum since the model's main explanation of technological innovation is property rights. Obviously, the existence of intellectual property rights does not automatically create new technologies. It could merely be a necessary condition of an environment that is conducive to innovation. While economic incentives that stoke the natural human drive of greed and ambition have remarkable explaining power, they do so within historical parameters and alone cannot explain the Industrial Revolution nor the "open source" phenomenon.

Determining the origin of technologies to find out how they arise is another one of those seemly insurmountable challenges that this paper takes on. Many different academic fields have long attempted to explain new technology, but part of the problem is that the "creative act" of invention is inexplicable, even to neuroscientists. In addition, historical examples do not seem to follow a single principle of invention, so any fashionable theory can easily be discounted with a single counter-example. Despite the infancy of current understanding, a review of the concepts surrounding technological advancement demonstrates their explanatory power when treated as a whole. Nicolas Crafts (1977/1985, p. 124-127) provides a nice classification of the different hypotheses breaking down how they attempt to explain invention: 1) the "heroic" approach; 2) the "response to stimuli" school; and 3) the "social determinist" view.

Before the theories are reviewed, it is prudent to follow in the footsteps of the best mathematicians who precisely define terms to clarify their use throughout this paper:

Invention versus Innovation

"Invention" is a rare event since it is the creation of a production or process for the first time. The two great fathers of innovation theory, Abbott Payson Usher and Joseph Schumpeter had unique conceptual formulations of invention. Usher (1954, p. 60-65) characterized it as an "act of insight" going beyond the exercise of normal technical skill, while Schumpeter (1934, p. 74-94) defined it as "the carrying out of new combinations". The term "invention" conjures up images of a lone genius struggling against the odds and has fed the popular notion of the heroic inventor. “Innovation”, on the other hand, is the improvement of an existing product, process or service. This term is more difficult to pin down as it comes in several forms and from various sources. Schumpeter commonly used the word innovation to denote an invention that is developed for commercial use. Robert Allen (1983) has coined the term “collective invention”, but this is actually innovation sourced by a collective. This paper will stick to the popular definition given above that emphasizes the application of new concepts and knowledge on an existing invention.

This distinction has led to a vigorous debate between two prominent economists, Robert Gordon and Joel Mokyr, at Northwestern University (Aeppel 2014). Gordon believes that our best days are over, since as the saying goes “everything that could be invented has been invented”. He asserts that mere innovation of existing technologies, such as the improvement of the telephone to the iPhone, will have a limited effect on economic growth since they are subject to diminishing returns. As an economic historian, Mokyr has seen many instances where the combination of inventions and innovations, such as today’s super computers, open the way to new inventions in the future. This was certainly the case for the invention of the steam engine where a virtuous circle was started, with the invention of scientific instruments that led to the barometer and the discovery of the atmosphere. Indeed, this paper will provide numerous examples where science and technology reinforce each other to foster new inventions.

Macro vs Micro Invention

Joel Mokyr distinguished between macro and micro inventions, using terms inspired by biology, to highlight their unique, yet complementary natures. Macro-inventions are game changing radical new ideas that have a tremendous societal and economic effect. They are extremely rare and are unpredictable in their occurrence as they are often the result of “strokes of genius, luck, or serendipity” (Mokyr 1990 p. 12). Examples of macro-inventions include the steam engine and its separate condenser, the light bulb and the semiconductor. They have a significant impact on economic growth as they provide a fertile ground for supporting micro-inventions.

Micro-inventions are “the small incremental steps that improve, adapt, and streamline existing techniques already in use, reducing costs, improving form and function, increasing durability, and reducing energy and raw material requirements” (Mokyr 1990, p. 12). Often, these are the components of the macro-inventions. For example, the D-valve improved the performance of the steam engine as it efficiently controlled the flow of steam. The original self-acting valves used the engine’s own steam power, robbing it of precious energy and heat. When one aggregates all of these small improvements, micro-inventions actually have a greater impact than the better-known macro-inventions. Micro-inventions are also very responsive to economic incentives and prices. They account for most gains in productivity, since as learning by doing and other improvements increase economic efficiency. However, continuous improvements are subject to diminishing returns and would eventually fizzle out without revolutionary breakthroughs.

A final concept in classifying inventions are "meta-inventions", which are inventions that generate inventions. They include revolutionary concepts, such as the secular observation of nature, scientific experiment and measurement, as well as intellectual property rights and are featured in this study for their role in advancing modern economic growth in the Western world.

The Heroic Inventor

Invention as a flash of insight, like James Watt's epiphany during his Sunday walk in the park, has a mass appeal that have turned men like Thomas Edison and Steve Jobs into heroes. The great American early economic historian of technology, Abbot Usher (1954, p. 60) described this approach where "the novelties that constitute the basis of social growth and development are (to be) attributed to the inspiration of genius", but concluded that it does not allow further explanation or analysis. While some inventors have been blessed with Eureka moments making spectacular contributions, the reality is much more complex. As another great economic historian, Carlo Cipolla (1972, p. 46) brilliantly summarized why, despite the achievements of Thomas Edison and other "great men", this approach alone in explaining innovation does not hold water:

> *Innovations are to history what mutations are to biology. Actually, innovations show a remarkable tendency to cluster in time and space, and this incidentally suggests that attention should not be devoted exclusively to the eccentric individual genius of the innovators, but should also be extended to the anonymous forces of the environment.*

Another problem with the "heroic theory" of invention is the concept of multiple discovery. The eminent sociologist Robert Merton (1973), famous for developing notable concepts such as "unintended consequences", "role model", "reference group" and "self-fulfilling prophecy", notices how similar discoveries or even inventions are made by scientists working independently. Most famous was the discovery of calculus by both Isaac Newton and Gottfried Leibniz, but the experience of Papin, Savery and Newcomen all inventing versions of the steam engine independently also discredits the idea that one particular individual is necessary in an invention. The history of many inventions shows that had they not been invented by X, they would have been made by Y. However, this connection is more difficult in some cases of great genius. It does not seem likely that had Shakespeare died in infancy, another author would have inevitably written the same masterpieces. Nevertheless, most inventions are best understood within the socioeconomic setting that gave birth to the inventor/invention.

Invention as a Response to Stimuli

Many economic and cultural historians subscribe to the theory that certain factors, such as scientific advances or the quality of entrepreneurship, affect the ability of inventors to react. Margaret Jacob (1997) emphasizes the central significance of science and the supply of scientific knowledge to technology. She also distinguishes the British environment where engineers and entrepreneurs could profit from applying scientific insight. Deirdre McCloskey's (2010) writings that underscore the importance of ideas and ideologies over economic or political institutions fall into this category. She notes that Britain's ideological environment, which fostered experimentation without fear of theological and political disapproval, feed the uptake of new techniques and inventions. Joel Mokyr (2009, p. 1) reiterated this idea in the opening lines of his masterpiece: "economic change in all periods depends, more than most economists think, on what people believe". He brilliantly synthesized Jacob's focus on science with McCloskey's emphasis on ideology with the concept of an "Industrial Enlightenment". Inventions flooded Britain as her artisans and engineers began to apply scientific knowledge to technology.

The "response" school of thought is exemplified by Rosenberg's (1974, p. 97) observation that "many important categories of human wants have long gone either unsatisfied or very badly catered for in spite of a well-established demand…a great potential demand existed for improvements in the healing arts generally, but…progress in medicine had to await the development of the science of bacteriology in the second half of the nineteenth century". While this view provides a powerful explanation for many inventions, it is difficult to verify it as a causal factor for invention. Economists have struggled with the proposition that invention flourishes in an environment that promotes technological knowledge. Some have countered with numerous examples where there is a clear demand for an invention, but the lack of knowledge of how to achieve it, may entice efforts, but not success. Similar to this paper's case study, Robert Allen (2009) examined three famous inventions to test the cultural response explanation. He found that the inventions were more related to Britain's unique wages and prices rather than her attitudes to innovation, which would imply that at least some inventive activity is socially or economically induced.

Socially Induced / Determined Invention

A "social determinist" view of invention places the emphasis on the social and economic needs over the individual, who is "merely an instrument or expression of cosmic forces (Usher 1954, p. 61). The idea of induced innovation was first proposed in 1932 by John Hicks (1963, p. 124) asserting that "a change in the relative prices of the factors of production is itself a spur to invention, and to invention of a particular kind – directed to economizing the use of a factor which has become relatively expensive". The view that Britain's growing population and factor scarcities stimulated technical change was pioneered by Habakkuk (1955, p. 154). John Nef's (1932, p. 170) classic, *The Rise of the British Coal Industry*, also emphasized how England's timber shortage in the Elizabethan era led to "a new industrial structure…built in England on coal (which) provided the basis for the industrialized Great Britain". This claim echoes the famous proverb, that "necessity is the mother of invention"[6].

Invention focused on the needs or desires of the market is well understood by today's marketers who realize the trick to a successful new product is creating what people love before they know they want it. This approach also makes sense to most entrepreneurs who would echo the argument that if there is no demand, there will be no payoff. Demand-side factors can easily be modelled by economists to show how the increased cost of a particular factor of production should induce inventive efforts in order to reduce the use of that input

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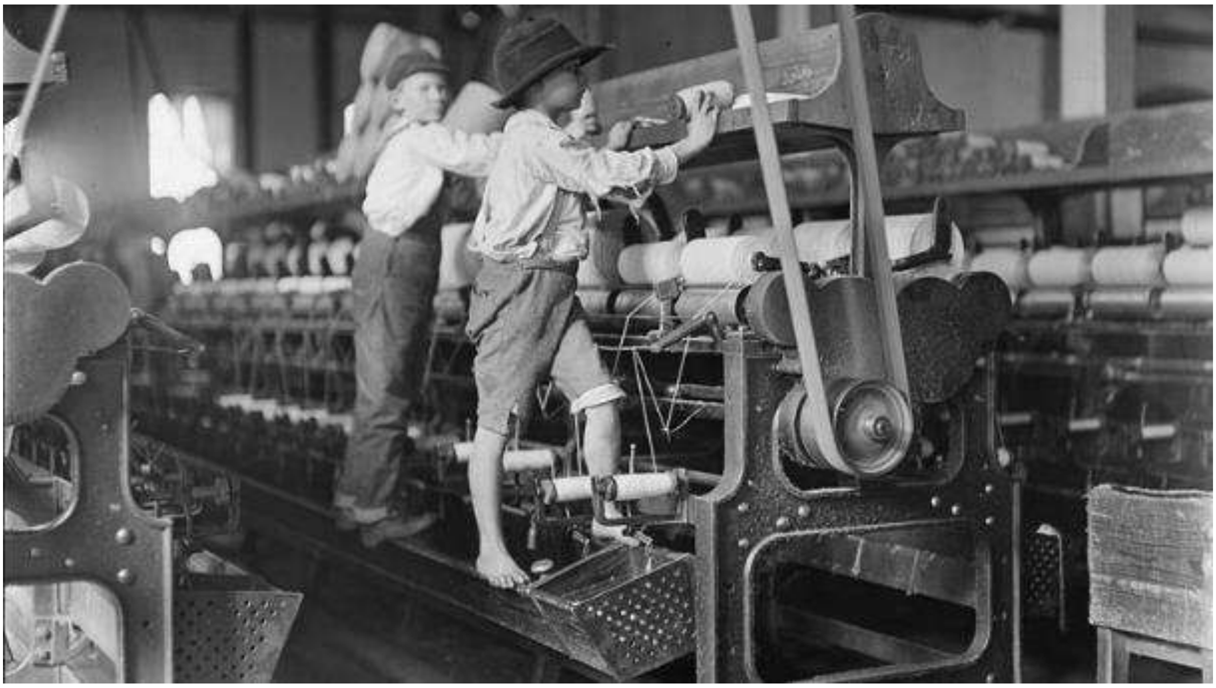
[6] The Norwegian version of this proverb is especially revealing, literally translated as "need teaches a naked woman to weave".

with a new cheaper substitute. Still, countless inventions have been created in the absence of economic incentives.

Expanding the scope of theoretical explanations from neoclassical economics to a multidisciplinary approach of the study of technology is better equipped to clarify the complexity of how invention occurs. Technological progress occurs in an environment with numerous contributing factors where it is difficult to isolate certain factors given their interrelatedness. The first impression of most students of the history of science and technology (useful knowledge) is how invention occurs under very uncertain conditions where unintended consequences lead to unknown outcomes.

The steam engine is a perfect example of how invention is more than an economic phenomenon. Its original use as a water pump was combined with rotative action to drive machinery. This allowed mills and factories to be located away from their traditional sites close to water or wind power. The steam engine and the resulting factories it powered employed the numerous families, including children, who migrated to the rapidly industrializing cities. This ultimately had numerous unforeseeable spillover effects on the environment, human health and the social fabric. Peter Gaskell (1833/1972, p. 33), a ferocious critic of the factory system protested the transformation of the very fabric of society, writing:

> *A complete revolution has been affected* (sic) *in the distribution of property, the very face of a great country has been re-modelled, various classes of its inhabitants utterly swept away, the habits of all have undergone such vast alterations, that they resemble a people of a different age and generation.*



A Synthesized Probabilistic Theory of Invention

The biggest problem with such socio-economic theories of invention is the significant time lag before their widespread application. This argument leveled by Musson (1972, p. 22-23) questions “if they were sociologically or economically ‘determined’, ‘inevitable’, and ‘necessary’, they should have been brought into widespread use immediately”. The idea that inventions have to wait for their time was eloquently summarized in 1945 by Vannevar Bush, the Director of the US Office of Scientific Research and Development (cited in Weightman 2015, p. vii):

> *Leibniz (1646-1716) invented a calculating machine which embodied most of the essential features of recent keyboard devices, but it could not then come into use. The economics of the situation were against it: the labor involved in constructing it, before the days of mass production exceeded the labor to be saved by its use, since all it could accomplish could be duplicated by sufficient use of pencil and paper. Moreover, it would have been subject to frequent breakdown, so that it could not have been depended upon; for at that time and long after, complexity and unreliability were synonymous…Had a Pharaoh been given detailed and explicit designs of an automobile, and had he understood them completely, it would have taxed the resources of his kingdom to have fashioned the thousands of parts for a single car, and that car would have broken down on the first trip to Giza.*

One of the foremost experts on technology, Nathan Rosenberg (1969), noted that all of this “on the one hand…yet on the other hand” economist-speak can be frustratingly difficult to pin down, leading to “extreme agnosticism” on the subject. Nicolas Crafts (1977/1985) urges readers to embrace the uncertainty and treat technological progress as more of a stochastic process. This approach can accept both the social and economic variables as well as the efforts and motivations of individual inventors, by assessing the force and direction these have on the probability of an invention occurring. A probabilistic theory of invention shows how inventions can become virtually inevitable after sufficient knowledge is focused and accumulated in the areas where they are most needed. This paper adopts that methodology, which can accommodate the deficiencies of a single theory, such as the time lag in the application of inventions, the existence of non-economic inducements as well as the importance of individual inventors.

Why England?

Many economic historians have asked the question closely related to this thesis: “why…did the decisive inventions take place in England?” (Davis 1973, p. 313). A review of the various explanations and theories are presented here to give a guide of the critical factors believed to give England the initial advantage. The most probable factors will be used in the more specific study of why the invention and initial development of the steam engine was dominated by the English.

The brilliant French scholar of English economic history, Francois Crouzet, provided the initial systematic comparison of the eighteenth-century English economy against “France as the leading continental power at that time… [in order] to bring out more clearly what factors were peculiar to England” (Crouzet 1967, p. 139). The importance of his study was underpinned by its applicability in explaining the Industrial Revolution.

Since the insight that a comparative study could provide important clues, a lively debate broke out between historians and economists, which highlighted various candidates for the prime causal factors (amongst the numerous contributors or correlations) for England’s dominance in innovation during the eighteenth century. Their views range from singling out Britain’s agrarian structural transformation (Kemp, 1969, p. 8) to Hagen’s claim that “differences in personality rather than circumstances are the central explanation of Britain’s primacy” (Hagen, 1967, p. 37). This well-worn idea of a unique national character, such as the British stiff upper-lip or holding the monarchy accountable (i.e. the Magna Carta and the 1689 Bill of Rights), has been brought into the twenty-first century with various modern takes on British peculiarity.

One of the more radical versions came from the brilliant non-conformist Deirdre McCloskey who set out in *Bourgeois Dignity: Why Economics Can’t Explain the Modern World* the idea that “change in talk and thought about the bourgeoisie … was probably of greater importance for explaining the modern world” (McCloskey 2010, p. 10). The realization that language can effect economic behavior has recently become popularized in some circles through behavioral economist Keith Chen’s (2012) TED talk “Could your language affect your ability to save money?”.

The idea that British culture was especially suited to birth the Industrial Revolution was given an evolutionary or biogenetic component in Gregory Clark’s *A Farewell to Alms – A Brief Economic History of the World*. His somewhat audacious thesis claims that “England’s advantage lay in the rapid cultural, and potentially also genetic, diffusion of the values of the economically successful throughout society in the years 1200-1800” (Clark 2007, p. 271). Clark echoes Max Weber’s view that the Protestant ethic was linked with the rise of capitalism. This is a difficult claim for economists to accept given their assumptions that all people are alike and will respond to the same incentives. However, Clark skillfully shows how institutions and incentives were largely unchanged prior to and during the Industrial Revolution, so the evolution of middle-class values is, according to him, the best explanatory variable.

William Rosen asserts in his eloquent story of the invention of the steam engine that the patent system was “the most powerful idea in the world” for its contributions to numerous British inventions during eighteenth century. He claims that the Industrial Revolution could only have started in the Anglophone world since it uniquely “democratized the nature of invention” by incentivizing an unpropertied populace to exploit their valuable ideas (Rosen, 2010, p. xxiii).

Rosen borrowed heavily on the ideas of Nobel Prize laureate Douglass North, who emphasized the role of the patent system, but also the broader body of property rights law. As the grandfather of institutional explanations of the Industrial Revolution, North cited a number of institutional factors that would cause the rate of innovation to accelerate, but the developments could be traced to a single causal factor, without which there would be no technological revolution. “It was better specified property rights…which improved factor and product markets…The resultant increasing market size induced greater specialization and division of labor, which increased transactional costs. Organization changes were devised to reduce these transaction costs and had the consequence of radically lowering the cost of innovating” (North 1981, p. 159). North, together with Weingast, later slightly backed away from the implication that without the Glorious Revolution, the British economy would have followed a very different path (1989, p. 831).

North’s (1990) work highlights the transactional costs theory of institutions, which recognizes that in addition to the regular production costs from inputs such as land, labor and capital, there are also costs in defining, protecting and enforcing property rights. This is precisely why informal institutions, such as norms, kinship ties and tradition as well as formal political or judicial institutions reduce uncertainty by providing life with a clear structure. These “rules of the game” drive down transaction costs, which would otherwise hinder economic growth. Institutions are only as effective as their enforcement mechanisms, which can be self-imposed, threats of retaliation or a third party sanction by society or the state. Regardless of which pivotal historical event(s), the institutional changes in eighteenth century Britain provided the “goldilocks” economic conditions for continual innovation contrasted with France whose institutions did not lead to a comparable capital market in order to mobilize savings and finance business activities. North and Weingast note that both the British and French governments were in an abysmal fiscal situation in the late 1600s, but “by 1765 France was on the verge of bankruptcy while England was on the verge of the Industrial Revolution” (North and Weingast 1989, p. 831).

A broad analysis titled “Institutions as a Fundamental Cause of Long-Run Growth” attempted to identify the fundamental causes of growth. Its authors borrow a powerful quote from North that “the factors we have listed (innovation, economies of scale, education, capital accumulation, etc.) are not causes of growth; they *are* growth” (Thomas and North 1973, p. 2). Acemoglu, Johnson and Robinson (2005, p. 389) further argue that:

> *Economic institutions are important because they influence the structure of economic incentives in society. Without property rights, individuals will not have the incentive to invest in physical or human capital or adopt more*

> *efficient technologies. Economic institutions are also important because they help to allocate resources to their most efficient uses, they determine who gets profits, revenues and residual rights of control.*

The authors use the rise of Britain's constitutional monarchy to illustrate "the role of political power in determining economic institutions". While they do not explicitly tie political reforms to the Industrial Revolution, they imply such stating "this form of government led to secure property rights, a favorable investment climate and had rapid multiplier effects on other economic institutions, particularly financial markets" (Acemoglu, Johnson and Robinson 2005, p. 453).

Robert Allen (2009) has put forth a very compelling argument that Britain succeeded due to her unique economic conditions on the eve of the Industrial revolution. Wages were high, while capital and energy were cheap. England's relative prices combined with the large market for manufactured products encouraged investment in new technologies, such as the spinning jenny in England, but not in France due to its relatively low labor costs. However, Allen makes an unrealistic assumption that new investments are only spurred by their cost-reducing potential. The reality is that investments decisions are based on their rate of return. Evidence suggests that while the spinning jenny was not as profitable in France as in England, it was still profitable (Horn 2012, p. 167). There are also many instances when relatively high wages do not spur investments in labor-saving technologies, such as the American experience during the Industrial Revolution period.

Despite their simplicity, other economic historians rejected single factor answers for "a multiplicity of factors – technological, social, economic, political, and cultural – which came together in the mid-eighteenth century to provide the stimulus of industrial advance. In all these factors, Britain had a slight advantage over France. But the advantage was qualitative rather than quantitative" (Kranzberg 1967, p. 299).

A broader view provided by Milward and Saul comparing Western European countries showed the weaknesses of singling out Britain as the uniquely suited location to be the birthplace of the industrial revolution in light of the diversity of the continental economies. "The more their history in the eighteenth century is considered, the greater appears the difficulty of finding a single factor in the British economy not present in some continental economies" (Milward and Saul 1973, p. 32-33). Proponents of the distinctive British conditions case could argue that it was the unique mix of factors in Britain that did the trick. Therefore, while France had a few ingredients and Holland others, only England had all an in the right quantities to bring about the industrial revolution. Unfortunately, this approach is tautological as it is true that Britain was indeed the instigator of the industrial revolution, so restating all the conditions present is committing a causal fallacy. It is also dangerous to use a British yardstick to measure the development of the continental economies, especially as they later instigated a unique technological revolution from a very different set of conditions.

Included in *The Economics of the Industrial* Revolution edited by Joel Mokyr, Professor Sydney Pollard provides a useful reminder that not all regions (within a nation) are created equal

(1985, p. 165-176). He demonstrated that while Britain contained a number of regions primed for industrialization, the continent also included such economies in parts of Belgium (Liege and East Flanders), France (northern and Alsace), Germany (Rhineland), Switzerland and the United States (eastern).

In the same volume, a different type of argument in the "Why Britain?" debate is postulated by Nicolas Crafts (1977/1985), where he questions the very question. If Britain and France both had equal probabilities to initiate the industrial revolution, but it occurred in Britain by random chance, then the question is inappropriate. Crafts (1977/1985, p. 127) makes a strong argument that "decisive innovations should be seen as the evolutionary outcome of a stochastic process". If this is the case, one cannot expect to find causal explanations for why England beat France to the invention party.

This argument may cause any other researcher to give up on answering the original question and shift to a stochastic analysis of the industrial revolution, but I believe Craft's claim to stem from the longstanding inability of economists to build credible models, let alone garner consensus, on the causes of the Industrial Revolution. Even if Britain just got lucky, it is worth identifying the systematic forces that caused her initial primacy.

Methodology

Overcoming Causality Issues

The Dangers of Econometrics

Determining proper causation has been the primary challenge of economic theory, especially as econometric tools merely identify significant correlations and not the true direction of causation. This was unfortunately exemplified in the aftermath of the 2008 Financial Crisis, when a paper called "Growth in a Time of Debt" influenced austerity movement politicians to justify harsh belt-tightening programs despite deep, widespread economic pain in the U.S. and Europe. The study was based on a data set from 44 countries spanning two centuries. Its authors, Kenneth Rogoff and Carmen Reinhart (2010) argued that countries with a debt to Gross Domestic Product (GDP) ratio that exceeded 90% experience a fall in median growth of 1%. This clear-cut conclusion was taken as fact and austerity measures were put in place in both the U.S. and Germany in order to bring the ratio below the magic 90% threshold.

In the spring of 2013, three years after the paper was written, a graduate student, Thomas Herndon, attempted to replicate the results as an assignment for his econometrics class. Shockingly, he found glaring data omissions and a goofy Excel spreadsheet mistake, which when corrected, led to the opposite conclusion; that debt can actually spur economic growth (Herndon, Ash, Pollin 2013). The implications of getting the direction of causation wrong in a scientific study used by government public policy makers have been tragic, especially for the unemployed in countries who have not been able to live up to the 90% GDP-Debt threshold (Spain, Greece, Italy) and had lost their international investment opportunities.

On closer examination of the data, it was clear that not all debt is created equal. The sluggish post-war economic growth in the U.S. from 1945 to 1947 was actually due to dismantling the war machine from decreased military spending and women leaving the paid workforce to return to their housework, which is not counted as GDP. The years following the initial contraction generated the strongest economic growth of the century. In fact, economists at the International Monetary Fund could not replicate the Reinhart and Rogoff findings after excluding anomalous periods, such as World War II (Pescatori, Sandri and Simon 2014).

The authors have since issued a response to the criticism of their paper. One statement was illustrative of the problem of econometrics' methodology: "we are very careful in all our papers to speak of 'association' and not 'causality'" (Rogoff and Reinhart 2013). This subtle clarification speaks to the dilemma in determining causality in economics. By merely reversing the causality, slow growth then becomes the *cause* of high debt levels. This opposite conclusion can also be supported using the very same data, by merely adjusting the timing of the effects. This raises serious concerns about the reliability of economic analysis, even when published in the field's most prestigious journals.

Econometricians, led by Edward Leamer (1983) and his celebrated article titled "Let's take the con out of econometrics", understood that in order to properly separate correlation from causation, they must first solve the conundrum of endogeneity bias. In layman's terms, this is an "identification problem" where one tries to work out whether a statistical pattern is truly caused by what we think. David Hendry's (1980) paper titled "Econometrics - Alchemy or Science?" vividly illuminated the challenge by demonstrating that rainfall caused inflation according to the standard methods of the time. New econometric techniques were developed or refined to repair the fractured environment where hardly anyone "takes anyone else's data analyses seriously" (Leamer 1983, p. 37). Where a controlled experiment is not feasible, which is usually the case in economics, the preferred method for dealing with correlation between the explanatory variables and the error term is using "instrumental variables". These instruments are basically an outside force that partly mimics the effect of a controlled experiment. As long as the instruments are related to the explanatory variables, but are uncorrelated with the error term (exogenous), the economist can better control the variables. This is much easier said than done, since there must be at least one valid instrument for every variable of interest and the criteria for validity is strenuous.

Instrumental variables can be found in quirks of public policy or history, such as the random nature of the US-Vietnam War draft (Angrist 1990). History is abundant with factors determined long ago that presumably could not be caused by events happening today. Unfortunately, the econometric approach still struggles in finding appropriate instrumental variables, and even when they are available, using them to estimate causal parameters is like choosing to let light "fall where it may, and then proclaim(ing) that whatever it illuminates is what we were looking for all along" (Deaton 2009, p. 10).

Randomized controlled experiments are the gold standard in scientific research, yet among economists, only the sub-discipline of behavioral economics uses subjects to find regularities in human behavior. Macroeconomists have not yet been able to convince an electorate to be used as a laboratory to test unproven theories, so the best they can do is use natural experiments. For example, Andrew Godley (2001) studied the different levels of entrepreneurship of Eastern European Jews who moved to London versus moving to New York at the turn of the twentieth century. As long as moving to one city over the other was random, this is a great natural experiment that would demonstrate how institutional environments affect entrepreneurship. In this instance, the causal effect can be measured as the “difference in the differences”. Unfortunately, such flukes in history when identical groups are subject to differing “treatments” which arise due to public policy or migration are rare and are still subject to subtle initial differences between the groups.

A preferred instrumental variable among development economists is a country’s colonial history. As long as colonies were claimed randomly throughout the world, it would qualify as an exogenous factor and would be suited as an instrumental variable. However, this kind of analysis breaks down if Britain and France intentionally calculated where they would colonize based on certain needs or proclivities. Without a good understanding of the historical context, an economist could paint a false picture of causation due to a non-random initial difference between the research subjects.

The use of econometrics, especially using older historical data that has been prone to errors, also leads to weak instruments. A highly celebrated book on why nations fail (Acemoglu and Johnson 2012) used mortality rates of the initial colonial settlers as an instrumental variable for their propensity to establish good institutions, i.e. those that protect property rights and minimize rent seeking. The authors claimed that favorable institutions were in greater demand in locations where settlers survive, thus if settlement was random, their mortality would qualify as exogenous. The accuracy of the historic mortality rates was called into question, jeopardizing the value of the instruments used (Abouy 2012).

The Strengths of Economic History

While economists pursue simple models that reveal underlying causal principles, historians allow for ample detail and context including evidence that cannot be mathematically modelled. Historical methods emphasize the chronological study of events linked to their outcomes. This often illuminates economic processes that do not lead to a steady-state equilibrium. This is exemplified in the concept of path dependence, which is the idea that ultimate outcomes are largely directed by historical starting points and any chance shocks along the way. Paul David (2000, p. 17), an early proponent of this evolutionary concept, reminds economists that historical case studies “may also be good fun, and when it is well done it typically manages both to provide entertainment and to satisfy particular points of curiosity”. This paper attempts to follow that advice, by illustrating the historical paths of the English and French economies as well as the stories of their fascinating inventors and the unique institutional environments in which they lived.

Economists critical of the overuse of econometrics, such as the 2015 recipient of the Nobel Prize in Economics, Angus Deaton, hit the nail on the head in the debate over striking a balance between accuracy and importance of the issue. Deaton (2009, p. 14) fears that economists will only tackle issues for which instrumental variables are available and avoid “thinking about how and why things work”. The methodology of historical analysis does not shy away from wide-ranging issues since it recognizes that there are many ways of establishing causality. As the saying goes: “correlation is not proof of causation, but it sure is a hint” (Tufte 2003, p. 4).

Historical methods including the use of contextual details, studying the recollections and motives of key individuals and weighing the plausibility of competing hypotheses may provide enough data to determine circumstantial causation. A rigorous study should also perform an external check whether its explanations for historical events actually fit the facts of the real world and not a theoretical construct.

This study seeks to emulate the best economic history has to offer by providing a detailed narrative which connects the dots of relevant events with causal links. It certainly overcomes the rigid view of *homo economicus* that implies all humans are consistently rational self-interested agents who optimally pursue their utility, in that the study leaves ample room for free will among its protagonists. Their biographies and even first-hand correspondence illustrate the thought processes and motivations of these great individuals.

Comparative Economic History

Comparisons are the foundation of economic inquiry, and for that matter all the social sciences. This is illustrated by some of the key questions social scientists have posed: “Why are some countries rich, while others poor?” “What is the effect of teacher-student ratios on test scores?” “Are democracies less likely to enter a war than authoritarian regimes?” A comparative historical analysis is especially useful in answering causal questions, such as which factors increased the probability of the Industrial Revolution first occurring in Britain versus France. Charles Ragin (1987, p. 70) highlights the value of a combined comparative analysis, which allows for the role of human agency, but also the structural factors, which both reflect actual historical processes.

The field of economic history arose from the fundamental question of “how the West grew rich?”. Economic history applies knowledge of economic processes to historical events using a unique combination of fields. While the study of history usually focuses on a case study, economics examines patterns within different events to determine whether they support a particular theory or model. Historians will typically answer a question in the form of a narrative. Economists, with their belief that everything can be reduced to a theory or at least a mechanical model, struggle with accepting any phenomena that cannot be repeatedly and quantitatively demonstrated empirically. While this paper will explain the importance of deductive and experimental science for its revolutionary role in advancing technology, it is realized that such a hyper-positivist methodology is inappropriate when studying humans and their internal decision-making processes. Before compiling and interpreting statistical results, a true and detailed understanding of the research subject is needed. This was widely understood in the wake of the global financial crisis of 2008, when many scholars and policy makers felt that a better understanding of economic history would have helped to call attention to some of the economies’ trouble spots (Economist 2015).

New economic history or “cliometrics” also has advantages in applying the empirical methodologies of economic modelling and quantification to such old historical questions, as the economic effects of slavery (Fogel and Engerman 1974) or the importance of steam engine technology on economic growth. However, cliometrics suffers from the same difficulties of establishing causation as its parent field of econometrics. It inherited the assumptions of economic laws that do not always fit with human activity, thus missing important insights from the humanities (Boldizzoni 2011). There is a large intellectual gap between the cliometric approach and the context-rich, in-depth, historical, small-N case study. Cliometricians will often disparage broader historical comparisons using three accusations: 1) using a deterministic approach versus probabilistic; 2) assuming there are no errors in primary data or secondary evidence; and 3) neglecting interaction effects. Rigorous historical comparisons can overcome such criticisms by providing a historical context that highlights the limits of the approach, the critical and transparent use of sources, and testing the theoretical model (Osinsky and Eloranta 2015, p. 17).

A multidisciplinary approach in the style of Karl Marx or Thorstein Veblen, who used complementary qualitative and quantitative methods in analyzing comparative historical cases, has a number of benefits. The comparative approach is a superior strategy for establishing causation, as one can easier isolate counterfactuals within the contrasts. John Stuart Mill first formulated the method of identifying commonalities of similar nations in order to investigate the underlying causes of a divergence (Osinsky and Eloranta 2015, p. 15). The literature review section highlights a number of comparative studies of the Industrial Revolution between England and France. However, the application of a particular case within the broader historical context provides further insight. For example, the steam engine was much more dependent on scientific knowledge than many of the other inventions of the eighteenth century. Therefore, this thesis delves deeper into how scientific knowledge was generated, disseminated and eventually employed in both Britain and France, than other general studies of the Industrial Revolution.

Using Econometrics as an Inspiration

Historical case studies are often criticized by quantitative researchers for their reliance on secondary evidence, such as texts written by other historians. They argue that differing inferences stem from the various interpretations of that evidence and it is unclear why one historical explanation is more favored than another. This can easily be overcome, even in a qualitative study, by utilizing a probabilistic approach (rather than deterministic), assuming there will exist measurement errors, and recognizing that there are often more than one cause which frequently generate interaction effects. In contrast to quantitative research, Savolainen notes that a case-oriented comparison allows “detailed contextualized examination of various causal configurations and interaction terms” (cited in Osinsky and Eloranta 2015, p. 14).

In order to avoid the *post hoc ergo propter hoc* fallacy[7], which is common among the explanations of the British Industrial Revolution, it is important to assess the relative magnitudes of the potential causal factors’ impact. While this paper has already addressed the difficulties in invoking *ceteris paribus* in a historical setting, Nicolas Crafts (1977/1985, p. 122-124) promoted this approach to “make inductive generalizations by looking for empirical associations between various features of economic life and the timing of the (innovation)”. One could envision a multivariate regression where each independent variable has a corresponding partial effect: $Y = \alpha + \beta_1 X_1 \dots + \beta_n X_n + e$. The dependent variable Y is the location of the invention of the steam engine, the Xs are the proposed causal factors and the βs are their effects, while e represents an error term.

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[7] Similar to flipping a coin and then explaining why it landed on heads.

It is important to remember that the partial derivatives (βs) can be either negative or positive, depending on the contributing or hindering effects. The interpretation of the error term is dependent on one's notion of the role of chance. The first being that the error term comprises the factors lost to history or are impossible to be included in the regression. This is the common understanding among economic historians who feel confident that they have identified factors critical to Britain's primacy in significant inventions of the Industrial Revolution. The danger of this approach is that it is prone to the same logical fallacy we are attempting to avoid. The favored interpretation of Crafts who emphasizes the similarities between England and France is that the error term is purely a stochastic error. In other words, if history was to replay itself, a twist of fate could cause the invention to occur in France.

While this exercise provides a useful framework in evaluating the variables involved in the invention of the steam engine, it would be impractical to perform a regression using quantitative data on the causal factors in France versus England. However, such a calculation could determine whether a set of institutions increased the likelihood of the invention occurring in one country over another or if it was a genuine stochastic event, which if given a different combination of personalities would alter the originating country. This paper seeks to perform that task using the methods of economic history, but taking inspiration from such a regression.

The Case: The Steam Engine – Step by Step

French Beginnings, English Domination

The idea that you could use steam when it condensed to produce a vacuum, allowing you to suck wealth out of the ground, was not new. In fact, the mere question "who invented the steam engine?" incites tremendous hostility. Italians will point to Giambattista della Porta, who designed a pump using steam power in 1606, while the French identify Salomon de Caus, who actually built a steam powered fountain described in 1615 (Arago 1839, p. 32). Finally, the British mention Edward Somerset (1663/1778), Lord Marquis of Worcester, who named a "water-commanding engine", suspiciously similar to de Caus', as invention number 68 in his 1663 pamphlet "A Century of … Inventions". Worcester was at the very least inspired by Solomon de Caus, whom he may have met at a Paris insane asylum, during Worcester's exile in France during the English Civil War (Stuart 1831, p. 10). It is surprising that Worcester failed in his attempts to start a public company that would "drain mines and marshlands" given his wealthy background and royal appointment as an inventor.

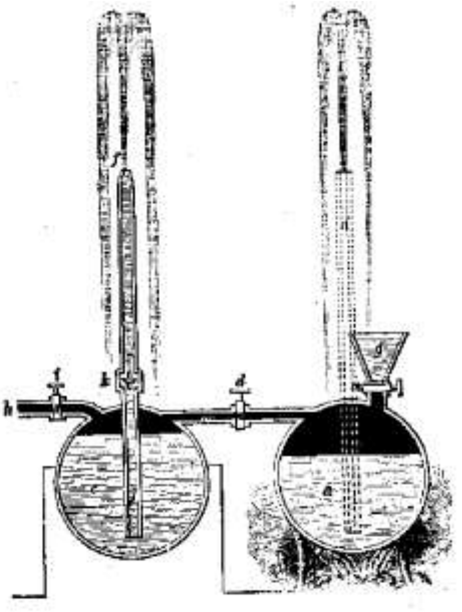
Figure 3 - Worcester's Steam Fountain (Somerset 1778)

Another Englishman named Sir Samuel Moreland made some sort of fire-driven water pump while he worked as an engineer for Charles II, King of England. Moreland took a different route with the invention by "endeavoring to obtain the patronage of the French Government towards a scheme which he claims as his own, for raising water by the force of steam" (Stuart 1831, p. 21). Moreland was likely prevented from doing anything with his idea in England since Worchester was granted a monopoly patent merely based "on his simple affirmation of his having made the discovery" (Stuart 1831, p. 22). While the 22-page business proposal to the King of France was unsuccessful, Moreland describes with mechanical accuracy the calculation of the volume of steam (Stuart 1831, p. 22). As steam condenses back into water in a sealed container, the vacuum it leaves behind takes about two thousand times the cubic area of water.

Denis Papin

While the science necessary for the steam engine stemmed from a pan-European intellectual enlightenment, the invention itself is almost exclusively a British affair. The exception is the French born Denis Papin, who built a model of the first piston steam engine. Papin worked as a secretary for the Curator of Experiments at France's counterpart to the Royal Society, the *Académie des Sciences*, which was actually an organ of the government. The curator, Christiaan Huygens happened to be at Versailles in order to repair a windmill that powered the palace's fountains. The two worked on air and vacuum experiments and while Huygens' dream of a gunpowder-powered piston did not materialize (and while it is said to be the first internal combustion engine, thankfully it did not blow up the two) their work provided the foundation for Papin's future experiments with steam (Bell 2008, p. 74).

On Papin's journey to the worlds' first steam engine, he crosses paths with both Robert Boyle, replacing Hooke as his assistant and later became Robert Hooke's assistant, during which time he invented the pressure cooker. In his demonstration to the Royal Society in 1679, he described it as a "machine for softening bones" (Papin 1681). It featured a brilliantly innovative safety valve that automatically released excess pressure. It remains the forerunner of today's pressure cookers used by chefs and autoclaves used to sterilize hospital equipment. By 1685, Papin became a religious exile as a Huguenot when Louis XIV revoked the Edict of Nantes, which previously granted them religious freedom. He travelled to Venice, where he was the director of experiments at the failed Accademia publicca di scienze, whose lack of financial support prevented it from becoming Italy's *Royal Society*.

Figure 4 - Denis Papin statue at the Louvre

Papin later joined fellow Huguenot exiles as a professor at the University of Marburg in Germany. It was there that he invented a pneumatic bed, a rotary pump and fan, a portable grenade-launcher, a submarine prototype *and* the first atmospheric steam engine. Published in 1690 in the *Acta Eruditorum*, he wrote to the chagrin of his former mentor Christian Huygens, "machines could be constructed wherein water, by the help of no very intense heat, and at little cost, could produce that perfect vacuum which could by no means be obtained by gunpowder" (cited in Dickinson 1939/2011, p. 10-11). The engine was a bit primitive compared to what would come, but it worked as steam in a tube pushed a piston up until it was grabbed by a fastener at the top, creating a vacuum under the piston. Then, when the steam condensed, atmospheric pressure pushed the piston back down. Strictly speaking, the device was a vacuum engine rather than a steam engine. Nonetheless, Papin is memorialized at the Louvre, holding his contraption that proved to be one of history's most important leaps of mechanical imagination.

Papin envisioned a ship powered by the motion of a row of pistons to paddle wheels, but he could not find financing for the project. He did find a patron, the Landgrave of Hesse-Kassel (Germany) in 1696, who wanted an engine that could lift water to be released into an elevated garden or fountain. Unfortunately, his prototype leaked from its joints and valves and the financing stopped (Winston 2010, p. 287).

Papin's most famous collaborator was the magnificent German mathematician, engineer and philosopher, Gottfried Wilhelm Leibniz, whom he met through Christian Huygens. In 1705, Leibniz sent Papin a sketch of a machine designed by Thomas Savery, which would raise water using steam power. This inspired him to revisit his own engine, which he worked furiously to improve and hoped to prove its superiority in a comparative trial of the two. Papin was ideologically opposed to patenting his inventions. He preferred to share his knowledge throughout the scientific community and wrote *The New Art of Pumping Water by using Steam* in 1707 in both French and Latin. His notion of a steam-driven paddleboat was also revived and he built a small mechanical-paddle boat he would ride to London, where he thought he could convince the Royal Society to equip it with a steam engine. Together with his family, Papin set out from the river Fulda in Germany, just in time for his "frenemy" Leibniz to give him a letter of recommendation to the Royal Society. Unfortunately, lacking a permit, the local guild of boatmen smashed up his means of transportation afraid of competition (Smith 1999, p. 139-147).

Papin's bad luck continued even after he finally made it to London, as the President of the Royal Society, Sir Isaac Newton, disregarded all his ambitious proposals. This could be because of the financial difficulties the Society faced at that time, but it could have also been another example of Newton abusing his position during his dispute with Leibniz over the invention of calculus[8]. Papin's failure to get more than an occasional ten-pound stipend from the Royal Society could also have been due to his foreigner status (Smith 1999, p. 143). From our modern eyes, he shows great business naivety for not securing a patent or commercially developing his idea.

Papin's difficult life illustrates both the genius lost due to religious persecution[9], as well as the challenges making a living as a seventeenth-century inventor if they were not supported by governmental or aristocratic patronage or a generous inheritance. Papin's correspondence is summarized as "evenly divided between generous sharing of his scientific discoveries and pleas for pensions, the latter wearing out his welcome in half a dozen countries" (Rosen 2010, p. 22).

Thomas Savery

The sketch of the steam pump that inspired Papin to continue his innovations was actually a design of the first commercial steam engine developed by an English military engineer turned inventor named Thomas Savery. The typical story told in the development of the steam engine is how Savery saw an opportunity to use the recent scientific discoveries on steam as well as vacuum and atmospheric pressure to be applied to the problem of pumping water out of mines. The engine created a vacuum by first pumping steam into a cylinder and then cooling it down. The atmospheric pressure would draw the water up to another cylinder where the pressure of steam itself pushed the water out. While he does deserve credit for translating

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[8] Newton appointed an «impartial» committee at the Royal Society, which found in his favor, tainting British opinion of Leibniz. Today, it is widely accepted that they independently invented calculus, while Leibniz's notation prevailed.

[9] Despite the end of major religious wars in Europe, persecution of scientists based on ethnicity or sexual orientation continued even into the twentieth century with Einstein's departure from Nazi Germany and the tragic suicide of Alan Turing in England.

what were before mere experiments into a “working” and practical model, Savery’s engine, which was really a suction pump rather than a true steam engine, had many limitations that ultimately prevented more than a handful being built. Why an engineer was able to develop the steam engine and make loads of money as a result, while a scientist with a superior design lived and died in poverty is a fascinating story that provides the first subtle contrast between Britain and France.

Savery is a great example of being in the right place at the right time. He seems to confirm the idea of startup entrepreneur Bill Gross (2015) through his analysis of over 200 companies, that timing is the single biggest reason why startups succeed. It was during Savery’s lifetime when the raw material for charcoal, which was the preferred fuel for heating, was consumed faster than it could be produced. Pit coal was initially a cheap alternative, as long as you did not have to dig deep enough that water needed to be drained. Pumps driven by waterwheels worked well to raise the water out of the ground, but most mines were not conveniently located by a river.

Savery had not only access to the science behind steam pressure and vacuum, but he also had the hindsight that his predecessors did not. He was also free from dependency on a wealthy aristocrat as he performed his experiments at a government facility called the Royal Office of Ordnance, whose sole purpose was to improve the technology of war. One location, Vauxhall, was described by Robert Hooke as “a place of resort for artists, mechanics… (where) experiments and trials of profitable inventions should be carried on” (Wallace, 1982, p. 39). It has also been described as the “seventeenth-century equivalent of the US Department of Defense Advanced Research Projects Agency, or DARPA”, where the internet was supposedly invented (Rosen, 2010, p. 24). The strategic interest of mining brought the steam pump into the realm of Vauxhall, which is precisely where Savery likely found Moreland’s notes as well as the critical calculation, without which, would make a working steam engine quite difficult.

Savery was also fortunate that enough time (about thirty years) had passed since the publication of Worchester’s invention pamphlet and his subsequent ninety-nine year patent. In 1824, Robert Stuart (1831, p. 34), the author of “Stuart's descriptive history of the steam engine” notes “during Savery’s life-time the Marquis of Worcester’s description had never been mentioned”. It seems amazing that Savery obtained his own fourteen-year patent in 1698 without any mention of the similar Worcester patent.

The Royal Society also provided somewhat of an understated recommendation after he demonstrated a small model of his engine, noting in 1699 “the experiment succeeded according to expectation, and to their satisfaction” (Stuart 1831, p. 35). In a genius marketing move, Savery (1702, p. 3-4) namedrops both the King and the Royal Society, hinting of their endorsements, in the introduction of his book The Miner’s Friend; or, An Engine to Raise Water by Fire. The book also contained a fictional conversation between him and a concerned miner where Savery refutes any objections made against the machine.

His engine did not quite live up to his inflated claims and even contemporaries called it “a useless Piece of Work” (Smith 1994, p. 2). Instead of a piston, like Papin’s design, it used water, which meant that it could only pump water. It had no moving parts, except for its valves, which had to be constantly opened and closed by a frantic operator. The boiler had to be refilled at least once per minute and the fire needed constant stoking. In fact, the water being pumped also needed to be boiled, wasting a lot of heat in the process. In addition, the machine was subject to the same limit that aggravated mining engineers and scientists alike – water can only be lifted about thirty feet using atmospheric pressure. In practice, this meant that Savery’s engine would have to be built no more than about twenty-five feet from the bottom of a mineshaft (Arago 1839, p. 41-44). The worst part was that the solder holding the engine’s cylinder had a melting temperature dangerously close to the high-pressure steam. In fact, an explosion of the boiler in 1705 caused Savery to discontinue building any more engines (Rolt and Allen 1977, p. 27).

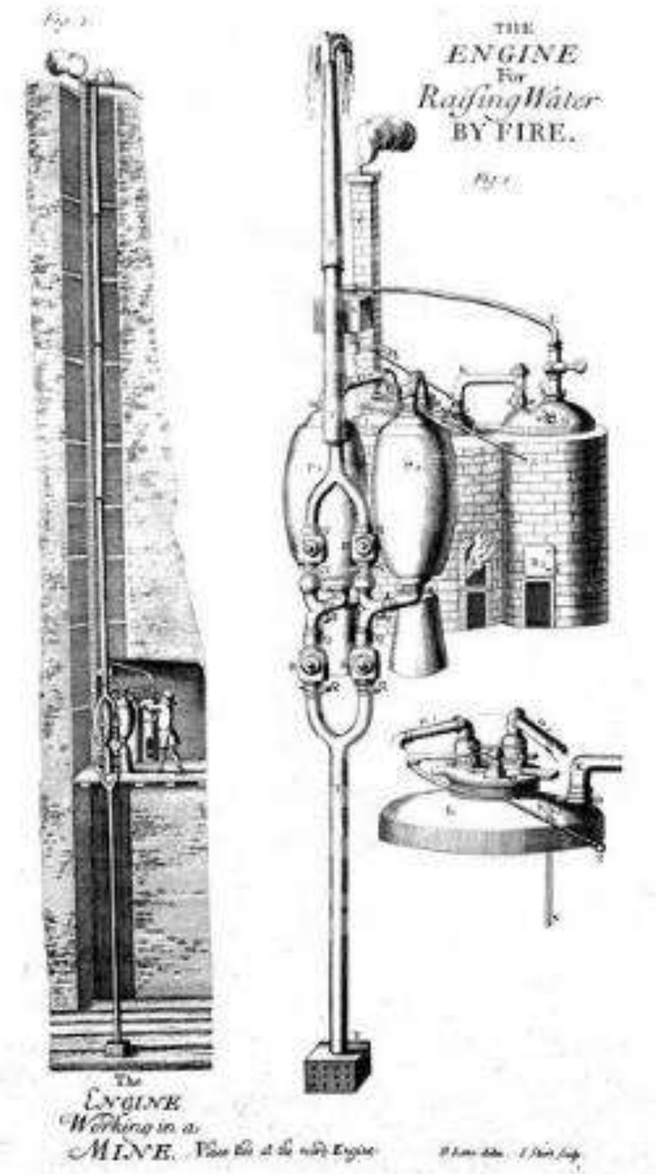

Figure 5 - Miner's Friend (Savery 1702)

Thomas Newcomen

Another English artisan who saw the promise of steam technology to assist in draining mines was Thomas Newcomen. Newcomen was an ironmonger who grew up around the tin and copper mines of Southwest England, where he sold his iron tools. He experienced how slow and inefficient the human, animal or even wind powered pumps were in raising water out of the flooded mines. Newcomen together with his plumber colleague, John Calley, concurrently had the same idea as Savery, but without most of its drawbacks. Firstly, Newcomen used copper boilers (the same expensive ones used by brewers), which could withstand high heat and pressure. Secondly, the engine would only rely on atmospheric air pressure, which was much safer than using high-pressure steam. Lastly, unlike Savery’s “friendly” machine, this was reliable, albeit quite slow. However, its dependability came at a cost.

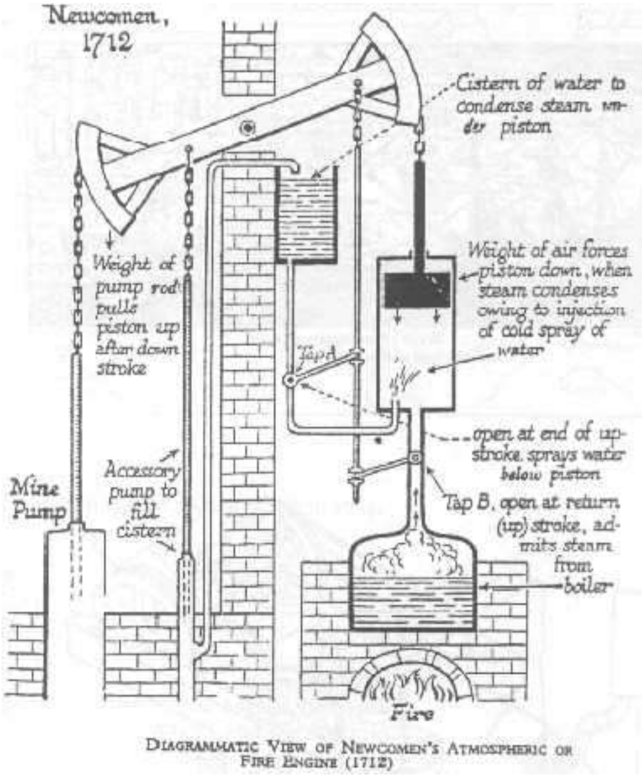

Figure 6 – illustration by J.F. Horrabin (Hogben 1938, p. 555, fig. 247)

The machine was a stationary leviathan with a gigantic pivoted beam that would seesaw back and forth housed in a brick building built next to the mine it was draining. It was the rocking beam that was the key to the whole thing. It was connected by chain to a piston encased in a cylinder. Steam filled the cylinder, which drove out most of the air. The cylinder was then chilled with cold water[10], which created a partial vacuum that forced the piston down, dragging the beam down with it. The other end of the beam worked the pump that lifted the water out. The weight on that side would bring it down as steam was filled into the cylinder again, causing the piston to rise again. Newcomen also figured out how to device the engine to be “self-acting” or automatic without the need to open and close valves for releasing steam or injecting water (Rolt and Allen 1997, p. 40-44).

Even though Newcomen likely developed his engine parallel, but ignorant of Savery’s designs, it was Savery who had a catch-all patent which forced Newcomen to sign a partnership agreement giving him part of the proceeds from Newcomen’s sales. This was a bitter pill for Newcomen to swallow considering the superiority of his design, as it could raise the same quantity of water using considerably less fuel and labor as two Savery engines working in tandem (Rolt and Allen 1997, p. 65). It is telling that Newcomen’s first engine was installed not in his native Devon, but rather at Dudley Castle in coal-rich Staffordshire. A cautious study identified about 300 engines as in use between 1712 and 1781 (Harris 1967, p. 147). While the engine was a success given its low construction costs and long life expectancy, it was almost exclusively used to drain coalmines or pump water to cities.

James Watt

Newcomen steam engines were working at coalmines all over England for about fifty years, but they still could not solve the Cornish mine-owners problem of flooded mines, given the enormous cost of transporting coal there. A new and more economical steam engine would have to wait for improved cast-iron methods as well as a stroke of genius. James Watt’s early life makes it seem like he is predestined to innovate the steam engine. He was working as an

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[10] An accident actually spurred an ingenious innovation to the machine, which probably brought its efficiency to the point that it could actually be economically feasible. Originally, the cylinder was cooled with a jacket of cold water, but when a leak cause cold water to go straight into the cylinder at the precise moment it was full of steam, it condensed instantaneously, causing a powerful vacuum to push the piston through the bottom of the cylinder and ended up in the boiler. He then realized that injecting cold water directly into the cylinder was much more effective producing 12 to 14 strokes per minute instead of 3 to 4 (Ferguson 1967a p. 102-103).

instrument-maker and technician at Glasgow University, in 1763 when he was asked to repair a model of a Newcomen engine used for demonstrations (Muirhead 1858, p. 83).

Figure 7 - James Watt and the Steam Engine: the Dawn of the Nineteenth Century (Lauder 1855)

Spending years tinkering with the device, he realized that its inefficiency was inherent in the repeated cooling of the hot cylinder with a jet of cold water. An efficient engine needed to do two jobs at once. It needed a cylinder boiling hot enough not to condense too early, but also become cold enough to actually condense the steam at the right time. It seems so obvious now, but it took the inspiration of a Scotsman in his twenties to produce a separate condenser. Watt actually describes that eureka moment as an epiphany he had while taking a Sunday walk in the Glasgow Green Park in 1765 (cited in Smiles 1874, p. 36):

> *I was thinking upon the engine at the time…when the idea came into my mind, that as steam was an elastic body it would rush into a vacuum, and if a communication was made between the cylinder and an exhausted vessel, it would rush into it, and might be there condensed without cooling the cylinder…I had not walked farther than the Golf-house when the whole thing was arranged in my mind.*

While Watt did keep the Sabbath day holy restraining himself from work, he had already turned his vision into reality just a few days later (Dickinson 1936, p. 64). However, it still took ten exciting years of dealing with patents, altering business partners and getting the parts just right before the first commercial machine was produced. Watt's improvement transformed the steam engine from a powerful water pump that was originally only economical at coalmines, to its extensive uses that had much wider significance on Britain and the world (Landes 1969, p. 102).

A Comparative Analysis of the Drivers / Causes Surrounding the Development of the Steam Engine from Papin (late 1600s) to Watt (late 1700s):

The literature review of explanations why England industrialized first provided numerous potential causes and drivers of her supremacy in invention. Many of those hypotheses are relevant to the investigation of the steam engine and will be used as the independent variables in this study. The first factor is the most foreign to economists, but nonetheless the advance of *scientific knowledge* offers a compelling explanation of the timing of the steam engine's invention. The next potential causal factor is the set of *resource endowments* present in Britain and France, including the presence of coal, a mining sector and the supply of critical inputs. Then, *economic institutions* such as the financing and patent systems are investigated for their role in incentivizing invention. Finally, various non-economic institutions like the *social classes* and their level of human capital, *political structures* and their influence on property rights and *religious influences* are all examined for their potential causality or contribution in the invention of the steam engine.

Science

The steam engine has done much more for science than science has done
for the steam engine – Lord Kelvin

Kelvin's adage is true in that the science of the time could not explain all the workings of the first steam engines and that later investigation led to the formulation of the laws of thermodynamics, pioneered by Carnot. Still, it is too simplistic as it disregards the key discovery of the vacuum, without which the steam engine would be inconceivable. The role of science in the invention of the steam engine can be seen as a mini-version of the larger debate whether the Scientific Revolution of the seventeenth century led to the Industrial Revolution of the eighteenth century.

Historians explored this link exhaustively in the 1960s and 70s, surprisingly concluding that scientific discovery did not lead to the technologies of the industrial revolution. A. R. Hall (1974) in asking "What Did the Industrial Revolution in Britain Owe to Science?" argued that inventions, such as the steam engine used very little scientific knowledge. He uses the tired argument that Watt's separate condenser did not need a theory of latent heat and that mathematics used in the engineering of the time was centuries old. He asserts that "the history of the Industrial Revolution in Britain shows amply how ready the technical innovators were to work out new ideas empirically when, as was then often the case, science had little guidance to offer" (Hall 1974). Unfortunately, Hall's analysis employed fundamentally flawed timing, using only the period of 1760 through 1830. His blunder is easily forgiven, as it is not always clear-cut when drawing a straight-line from a scientific discovery in one century to an applied technology in subsequent centuries. But, as this paper will soon establish, the scientific knowledge crucial for the steam engine was discovered prior to eighteenth century.

On the other side of the "science matters" debate is the authoritative study by A.E. Musson and Eric Robinson (1969), who documented in detail, a connection from the new science of Robert Boyle and Isaac Newton to its application by the early industrial inventor-engineers. While they do not claim that science was the most important factor of the Industrial Revolution, they emphasized the neglected link between pure and applied science (which eventually leads to technology). A more recent example of this approach is found in the writings of Margaret C. Jacob. She defends the position through sophisticated inference that the growing audience for science occurring at the same time as the application of that knowledge demonstrates how scientific investigation was instrumental in the technological development of the time. She coined a clever metaphor to explain the interrelatedness of the science-technology relationship calling them "fraternal twins, born into a family particularly eager for profits and improvement: they have different personae, different looks, but are still profoundly related" (Jacob 1997, p. 9).

When limiting the debate to the invention of the steam engine, there is a clear and direct link from seventeenth century science to Papin and subsequent steam engines. The upcoming story outlining the discovery of steam and vacuum power underscores the fact that virtually all the responsible scientists were Western European, beginning with Italian and German, while the later critical breakthroughs were largely Anglo-French.

The Science of Steam and Vacuum: a short history

Hero's Engine

The knowledge that water expands when heated enough has been with humanity for thousands of years. In fact, the very first invention associated with the steam engine was made in the Egyptian city of Alexandria almost 2,000 years ago by the Greek mathematician Heron. It was called the *aeolipile* or a Hero engine, which used steam exhaust from vents to cause a sphere to rotate. The name is a combination of the Greek word Αἴολος and Latin word pila, to mean "the ball of Aeolus", who was the Greek god of the air and wind.

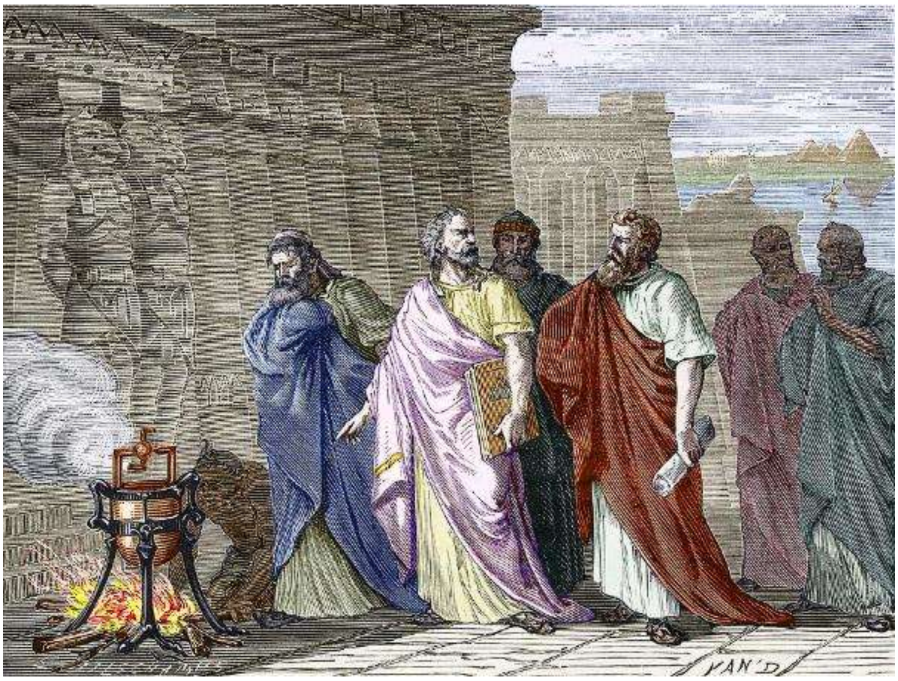

Figure 8 - Hero of Alexandria (Terry 2013)

Heron was undoubtedly antiquity's best toy inventor, many of which were documented in one of his seven books called *Pneumatika*, including "Temple Doors Opened by Fire on an Altar," and "A Trumpet, in the Hands of an Automaton, Sounded by Compressed Air". While these ancient contraptions are fascinating to think about, it was a single idea hinted at in the book's title, which was critical in the creation of the first steam engine. An example from childhood best illustrates the idea that not only moving air, but also the absence of air exerts pressure. As a child places their finger on top of a straw filled with liquid, they are inadvertently creating a vacuum by sucking the air out of the straw.

In a sad twist of fate, this idea contradicted the theory of Aristotle (the very tutor of Alexandria's founder) that there is no such thing as a vacuum, and thus this vital insight was lost for fifty generations. Europe can thank Islamic science, for at the very least preserving ancient knowledge, such as *Pneumatika*, which was eventually translated from an Arabic translation to Latin in the thirteenth century (Rosen 2010, p. 8). Before we leave the captivating world of Heron, it is thought provoking to note that the aeolipile, like many inventions prior to the Industrial Revolution, inspired no further invention and was merely used to entertain the rich and powerful. In fact, for most of human history, successful inventors were either wealthy enough by birth or were dependent on patronage provided by entertaining or glorifying their benefactors.

Torricelli and Atmospheric Pressure

While the aeolipile only depended on the expansive force of steam, the steam engine's secret ingredient of the vacuum was not revealed to Europe until the spring of 1644 at the ground zero for both the Renaissance and the Scientific Revolution, Florence. It was there Galileo Galilei chose to live under house arrest for his heretical opinions that the earth revolves around the sun. In fact, Galileo spent his final three months alive discussing physics together with a young admirer named Evangelista Torricelli. Torricelli's life provides a fascinating glimpse into the world of medieval scientists. He was born into a very poor family, but was talented enough to be taught by his uncle, a monk. He later studied under a Benedictine monk who worked on hydraulic experiments and undertakings, funded by the Pope Urban VIII (Jervis-Smith 1908, p. 9). In exchange for his tuition, Torricelli worked as a secretary and later as a substitute teacher for the monk.

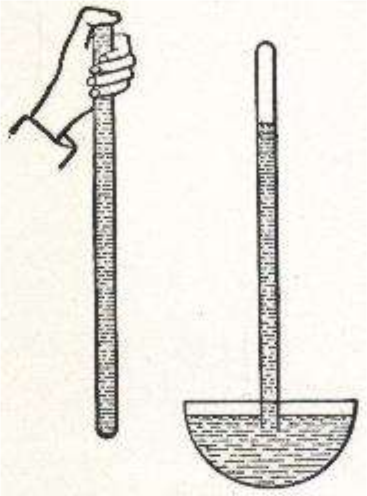
Figure 9 - Torricelli's experiment

Torricelli eventually succeeded Galileo as the court mathematician to the Grand Duke Ferdinando II of Tuscany, which was like professor of mathematics at the Florentine Academy. Galileo's revolutionary attitudes towards experimentation and his ability to ignore established authorities, especially Aristotelianism, must have rubbed off on Torricelli. It was at the behest of the Grand Duke, whose engineers struggled with breaking the nine-meter limit of suction pumping water, that Torricelli resurrected the idea of the vacuum through his experiments using mercury in the same way the child sealed the top of the tube/straw. Unlike Coca Cola in a straw, Torricelli noted that the mercury sunk a bit, leaving a space at the top. He then observed that the amount of space varied at different times of the day and month, accidently inventing the first barometer. He reasoned that the variance must be caused by “changes in the atmosphere, which is sometimes heavier and denser and at other times lighter and thinner” (cited in Jervis-Smith 1908, p. 16). Torricelli was not as brave a Galileo and quickly shifted his study to geometry when the religious authorities became hostile, smelling the threat to their Aristotelian worldview. Nevertheless, while vacuum would keep the mercury in the tube, the idea leaked out to scientists across Europe.

Magdeburg hemispheres’ vacuum

The enormous power of the atmosphere was amazingly demonstrated in the aftermath of the Thirty Years War in the famous Magdeburg hemispheres. Their inventor, Otto Gericke, was born in Magdeburg in 1602 (which would have been like my fellow NMBU student Mohamed Abdisalam, who was born in Somalia in the early 1980s). Magdeburg was sacked in 1631 by Catholic imperials for its Protestant resistance, killing more than twenty thousand. Otto himself recalls that when civilians ran out of loot to give the soldiers, they “began to beat, frighten, and threaten to shoot, skewer, hand, etc., the people” (Helfferich 2009, p. 109). By the time the Peace of Westphalia came about seventeen years later, less than 500 war-weary survivors lived in the city, which once was one of the largest in Germany. Otto returned home from his studies to help rebuild the city using his military engineering experience.

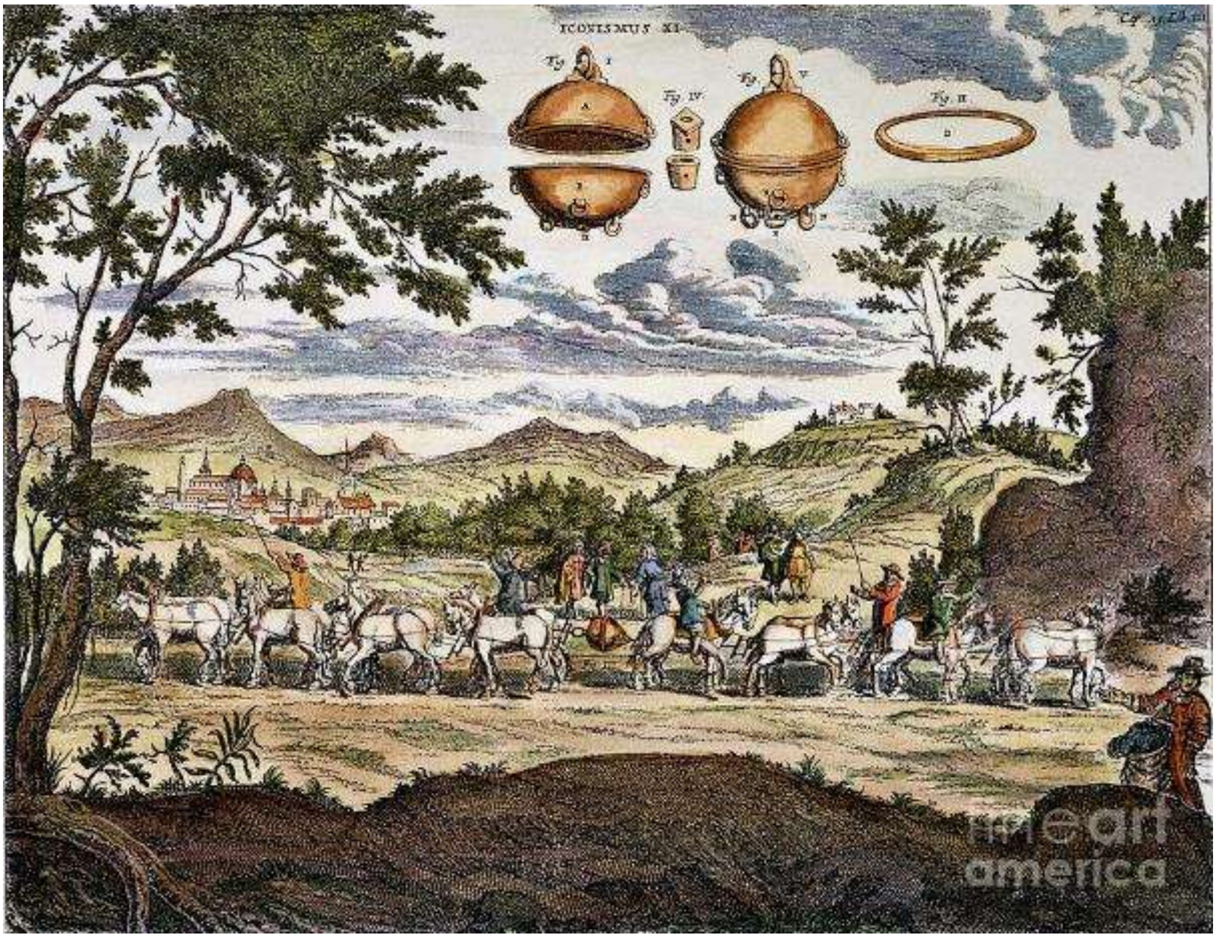

Figure 10 - Magdeburg Hemisphere, 1672 (Granger 2012)

In a spectacle that likely resembled the excitement of Steve Jobs unveiling the iPhone, Gericke dramatically demonstrated the vacuum pump with two hemispheres whose air was sucked out and sealed, only to be held firmly together by the air pressure of the surrounding atmosphere. In fact, the vacuum was so strong that reportedly thirty horses, in two teams of fifteen, could not break the vacuum seal of the hemispheres. It is a mystery as to why the gimmick actually worked, as the vacuum force generated would have been an impressive 4,400 lbs., which could easily have been broken by thirty horses. The risk or showmanship paid off as he became famous enough to be knighted by the Emperor Leopold I and featured in another book with the infamous title *Mechanicahydraulica-pneumatica*, written by the German mathematician Gaspar Schott (Conlon 2011, p. 7).

Machina Boyleana

The story of the scientific discoveries leading up to the steam engine travels through Schott's book from Continental Europe to a wealthy British aristocrat, named Robert Boyle, who was educated at Eton College and devoted his life to scholarship. He pioneered the experimental scientific method while delving into alchemy and subsequently becoming the founder of modern chemistry. Fortunately for this story, he became fascinated by Guericke's air pump and hired an equally brilliant, but considerably less wealthy student, Robert Hooke, to help him improve the pump. To assist in understanding the properties and characteristics of the vacuum, Hooke built the aptly named "*machine Boyleana"* in 1659, whose glass case allowed them to investigate and manipulate what was happening within the vacuum chamber. The two performed various types of experiments, including depriving a bird of air in the pump, as depicted in the painting below, composed over one hundred years later.

Figure 11 - An Experiment on a Bird in the Air Pump (Wright 1768)

Their findings were published in *New Experiments Physico-Mechanical, Touching the Spring of the Air and Its Effects*, which documented Boyle's law, a discovery that would later be used by James Watt in improving the efficiency of the steam engine. The law states that if you double the volume of gas, the pressure of the gas is cut in half ($P_1V_1 = P_2V_2$, for the symbolically inclined). In other words, if you allow the gas more room, the pressure goes down and if you squeeze it into less space, the pressure goes up. They also found that increasing the temperature of a gas would also increase pressure, providing the final bit of scientific knowledge needed to invent the first steam engine (Shapin and Schaffer 2011, p. 26-27).

The Industrial Enlightenment

It is clear that scientific concepts essential to the steam engine, such as the vacuum, were just as available in France as in Britain. However, when a more nuanced approach to the "science matters" debate is taken by viewing of science as a method or culture, rather than mere knowledge, differences between the two countries become apparent. In the widely read *A History of the Sciences*, Stephen Mason explains "Whilst the *content* of scientific knowledge did not have much influence upon the development of industry up to 1850, the *method* of science did" (1962, p. 503) (italics added for emphasis). Indeed, the technologies of the Scientific Revolution were largely scientific instruments themselves (i.e. telescopes, clocks, von Guericke's hemispheres, Hooke's vacuum machine and to a certain extent, navigational instruments) and not necessarily practical devices. If the steam engine was one of few exceptions of a direct science to technology link during the eighteenth century, it seems preposterous to completely dismiss science's role in the Industrial Revolution. But, if theoretical science was its only precursor, why was it not invented fifty years prior, when the necessary scientific principles were first discovered?

The preeminent economic historian of the Industrial Revolution, Joel Mokyr (2002), provides a compelling answer in his idea of a bridge between Europe's natural philosophers (scientists) and its industrial innovators, called the "Industrial Enlightenment". While the term perfectly fits the English experience, it refers to both the primarily French intellectual Enlightenment and the decidedly British Industrial Revolution. It focuses on the belief "that material progress and economic growth could be achieved through increasing human knowledge of natural phenomena and making this knowledge accessible to those who could make use of it in production" (Mokyr, 2009, p. 40). The Industrial Revolution's link with the Scientific Revolution can be traced from three interrelated phenomena, which Mokyr cites as incidental spillover effects from the scientific endeavor of gaining knowledge: scientific *method*, *mentality* and *culture*.

Scientific Method: the Dethroning of Aristotle and the Church

While the science of the eighteenth century could not theoretically explain how the first steam engines actually worked, it did provide a new and powerful way of asking questions. Scientific inquiry was essentially syllogistic, as thinkers would contemplate opposing ideas within the church sanctioned framework. The Scientific Revolution gets its revolution from the dramatic change from studying the word of God[11] to utilizing empiricism as the most reliable path to truth. However, the transformation did not start out searching for truth; rather it started

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[11] At least as conveyed by the Roman Catholic Church.

looking for mistakes. As long as scientists unconditionally accepted church sanctioned knowledge, such as Aristotle's view on physics and biology and Galen's insights on medicine, science would be stuck in the middle ages. Galileo is the most famous revolutionary for his writings against the Aristotelian geocentric view that the earth was the center of the universe from which all the stars and planets revolve around. Gregory Clark (2007, p. 145) eloquently calls his heresy trial and condemnation "an exemplar of the reign of superstition and prejudice that was responsible for the long Malthusian night". A less-known, but equally revolutionary refutation of Aristotle was provided by the Italian biologist and poet Francesco Redi, referred to as the "founder of experimental biology", who challenged the prevailing theory of spontaneous generation with his experiments which showed maggots come from the eggs of flies (Bernstein and Bernstein 1982, p. 17-19).

The massive shift in which scientists trusted their own observations over those authorized by the church led to an early experimental method that was at the heart of the Scientific Revolution. The distrust extended also to contemporaries as illustrated in the Royal Society's motto *nullius in verba* ("on no one's word"). Until a conclusion could be replicated, you could not really trust it. Another epistemological transformation was that knowledge was no longer absolute. In other words, theories could be replaced by new and better ones, and not through logic alone, but through experimentation.

Scientific Mentality: the Taming of the Natural World

Another remarkable paradigm shift was the newfound faith in the orderliness, rationality and predictability of natural phenomena (Parker 1984, pp. 27-28). This meant that scientists could discover the formal rules that govern nature, which they did by breaking the world down into its component parts and thinking of the world like a machine. The use of mathematics comes into play as a powerful tool in describing and analyzing nature's rules. This also opened the door to the idea that technology can manipulate the physical environment. This view, that nature and manufactured technology were subject to the same laws, was famously written by Newton in *Principia*.

While most of these revolutionary scientists professed a thoughtful belief in a divine creator, they sought to separate scientific ideas from religious ones. While the church of the time claimed to know everything worth knowing about nature with its wholehearted adherence to the Aristotelian view, these non-conformists challenged this tradition with an open mind and willingness to experiment. Their scientific mentality allowed them to abandon the conventional supernatural doctrine when systematic experimentation and investigation provided a different explanation.

Scientists exerted considerable intellectual energy on describing phenomena they could not yet understand using the three Cs of scientific observation – counting, classifying and cataloging. Carl Linnaeus exemplified this spirit in performing minute descriptions and measurements of nature. The title of his first book says it all: *Systema naturæ per regna tria naturæ, secundum classes, ordines, genera, species, cum characteribus, differentiis, synonymis, locis* (or System of nature through the three kingdoms of nature, according to classes, orders, genera and species, with characters, differences, synonyms, places). It was not the measuring that made a difference, but the emphasis on accuracy, thoroughness and reliability of those measurements (Heilbron, 1990).

The scientific mentality also had a profound impact on the engineers and technological innovators of the time. Shortly after the first Newcomen steam engine was installed, Henry Beighton, the editor of the *Ladies' Diary*[12], published a table listing the horsepower of the various engines given the diameters of their cylinders. Again, the title illustrates this new approach: *A Calculation of the Power of the Fire (Newcomen's) Engine shewing the Diameter of the Cylinder, for Steam of the Pump that is Capable of Raising any Quantity of Water, from 48 to 440 Hogsheads an Hours; 15 to 100 Yards*. One of the first studies of the steam engine was written by Desaguliers, a British natural philosopher and engineer of French Huguenot origin, who served as Isaac Newton's assistant at the Royal Society. Desaguliers subsequently wrote in the widely read applied science *Course of Experimental Philosophy*, "Mr. Beighton's table agreed with all the experiments made ever since" (Desaguliers 1744, vol. 2, p. 534). Not only could the measurements be reproduced, but also they can be used to improve the efficiency of the machine, even when the science behind it was not fully understood. In fact, James Watt extensively studied that same book later stating that his "knowledge was derived principally from Desaguliers" (Russell 2014, p. 132).

Scientific Culture: Francis Bacon's Vision and the Royal Society

The Industrial Enlightenment gets its industry from the Baconian belief that research should be directed to the practical problems of the time, such as medicine, manufacturing and navigation and that it should be made available to society's innovators (Jacob 1997). Bacon understood that science only becomes powerful when it becomes a social enterprise with free flow of information among its investigators. He advocated state support of empirical science (discoveries and techniques) to nurture its practice and dissemination, since it was the state that benefited most from innovation.

In the posthumously published *The New Atlantis*, Bacon vividly describes what today would be considered a government-funded research and development facility. Salomon's House was home to hundreds of investigators, with Miners who performed experiments and "Benefactors" who looked for applications for the new discoveries. Interestingly, "Benefactors" were not artisans or craftsmen, since they sought innovations that would provide the highest value to the state. In fact, Bacon did not believe inventors should be granted patents or any property rights that would enrich them.

In honor of Francis Bacon and inspired by his Salomon House and the French Montmor Academy, Robert Hooke and other natural philosophers received a royal charter from the king, establishing the *Royal Society of London for the Improvement of Natural Knowledge* in 1663. In contrast to the French *Académie des Sciences*, the Royal Society was not a state organ and regularly accepted many who were not professional scientists. In its early years, it provided research and practical information without government support. "The business and design of the Royal Society is to improve the knowledge of natural things, and all useful Arts, Manufactures, Mechanick practices, Engines, and Inventions by Experiments" (cited by Lyons, 1944, p. 41). In contrast to the image of the arrogant theoretical astrophysicist depicted in the brilliant modern adaptation of *Cosmos*, Robert Hooke was actually the first "working class" or

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[12] or *Woman's Almanack*, which was a London periodical designed for "the fair sex" which sometimes included puzzles dealing with Newtonian infinitesimal calculus – a far cry from the tabloids of today.

salaried scientist in Britain as the curator of experiments. He was memorialized as "the greatest Mechanick this day in the world" (cited by Eds. Chapman and Kent, 2005, p. 1).

The Lunar Society of Birmingham

The inventions of the Industrial Revolution may owe a debt to the Royal Society, but it was the provincial areas that established more practical scientific academies that provided the perfect meeting places for Britain's innovators. The Lunar Society of Birmingham, named as the "lunatic" members met informally on the Monday nearest the full moon so they had enough light to ride home. The society was comprised of a spectrum from industrialists to engineers to actual scientists. James Watt and most of his innovative contemporaries were members, including his business partner Matthew Boulton, his chief steam engine engineer William Murdoch and his iron supplier John Wilkinson. Most members were not university educated and most were Nonconformists, putting them outside the Establishment. They echo a theme we will see again when examining religious institutions; that apparent disadvantages can actually become an inadvertent strength. They were free from the constraints of the stuffier formal institutions and their deference to tradition. Unlike the Parisian salons or English coffeehouses, they did not discuss religion or politics (Uglow 2002 p. v).

This influential network of the first leaders of the Industrial Revolution actually racked up numerous scientific achievements, despite them not practicing "proper" science. They exemplified the Industrial Enlightenment as they applied scientific principles to technological innovation. Jenny Ulgow (2002, p. 210) eloquently described them as:

> *pioneers of the turnpikes and canals and of the new factory system. They were the group who brought efficient steam power to the nation…All of them…applied their belief in experiment and their optimism about progress to personal life and to the national life of politics and reform…They knew that knowledge was provisional, but they also understood that it brought power, and believed that this power should belong to us all.*

The Society should not be seen as a significant contributor to the Industrial Revolution, but it was another arena where its brilliant heroes could meet and disseminate knowledge. Potential inventors could also use the numerous provincial and school libraries that started sprouting up in the mid-eighteenth century. There were also informal venues, such as coffeehouses, which were promoted in 1699 by John Houghton who wrote "for an inquisitive man, that aims at good learning, may get more in an evening than he shall by books in a month" (cited by Cowan 2005, p. 99). Masonic lodges and taverns also provided the setting for public lectures on technology or lay science. This paper has already mentioned the contributions of John Desaguliers, who conducted lectures across the country paid for by the Royal Society. He was not a pioneer himself, but as a founding member of the British Freemasons, he was instrumental in diffusing ideas, such as the advantages of overshot water mills (Hills 1970, p. 98). He embodied the Industrial Enlightenment in that he made useful knowledge available to Britain's innovators.

James Watt's debt to science

An improbable amount of events in James Watt's life up to his invention of the separate condenser steam engine seems predestined or perfectly placed to prepare him for that achievement. First, he had both academics and mechanics in his blood, with this grandfather a mathematics instructor; his distinguished mother's side had connections with Glasgow University; and his father was a jack-of-all-trades. Raised a Presbyterian, he followed in the footsteps of other non-conformist young men, informally educated with a focus on mathematics. His run in with the London craft guild, who barred him from an approved seven-year apprenticeship, taught him the silliness of treating knowledge as a zero-sum game. He was later blocked by the fearsome sounding "Incorporation of Hammermen" guild from setting up a shop in Glasgow.

At the age of twenty, the gods smiled on Watt again as a Scottish merchant/scientist, Alexander Macfarlane, who lived on Jamaica, bequeathed his sizeable astronomical instrument collection to his alma matter, Glasgow University. During the several week trip from the Caribbean to Scotland, the telescopes and quadrants were damaged from the salt air and rough handling. Through Watt's mother, James had already met Robert Dick, the professor of natural philosophy at the university, who would be responsible for the sea-damaged Macfarlane collection. Watt was offered a job to repair the instruments and joined the great minds of the University of Glasgow faculty as their mathematical instrument maker, which provided him a workshop. He was originally seen as just another skilled craftsman at the university, but he quickly showed there was more to him than that.

John Robison who later became a distinguished scientist[13], described when he first met Watt as a university student in 1758: "I saw a Workman and expected no more – but was surprised to find a philosopher…was rather mortfyd at finding Mr. Watt so much my superior" (cited in Burton and Tann 2012, p. 87). He also recalled how "everything became Science in (Watt's) hands…he learned the German language in order to peruse Leopold's *Theatricum Mechanicum*…every new thing that came into his hands became a subject of serious and systematical study, and terminated in some branch of Science" (cited in Robinson and Musson 1969, p. 25). Robison gave an example of when the local Masonic lodge needed an organ and Watt learned the study of harmonics and vibration in order to build a perfect organ (Robinson and Musson 1969, p. 28).

The next inadvertent preparation for James Watt illustrates his background as a master artisan without the means to support a lifetime in the passionate pursuit of scientific discovery. In the winter of 1763, Watt is given the most providential job of his career, when he is asked to repair a model of a Newcomen engine. The model would stop working after only two or three strokes. Watt loved a puzzle and quickly found that the problem was intrinsic to the model's size. Just as model designs can easily fail after being built in life-size if the supports cannot bear the true weight, a miniaturized model can also fail when scaled down. Watt did not stop there though as he sought to explain why the model used much more steam than could be accounted for.

Watt found a mentor in Professor Joseph Black, the university's foremost scientist who first established the principle of latent heat. While the principle may seem arcane and unrelated to technology, it had a profound impact on the evolution of the steam engine. Black was fascinated with how water reacted from the transition of one property to another (liquid –

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[13] Perhaps more famous today for his off-the-wall theory about the French Revolution being caused by a Masonic conspiracy.

solid – gas). Questions such as why ice did not completely melt immediately when heated or why boiling water does not increase in temperature no matter how hot the fire underneath. Simple experiments into these phenomena led to his theory that latent heat is gained or lost between the changes from gas to liquid or solid to liquid (Jacob 2014, p. 28-29).

There are fierce debates over whether Watt became wealthy by taking advantage of Black's theory in his steam engine, but a cursory read into the letters between the two demonstrates what a great scientist Watt was in his own right (Watt and Black 1969). It is not generally known, but Watt actually assisted Black in establishing the theory through his own experiments (Burton and Tann 2012, p. 87). Watt did take advantage of Black's knowledge, but far from a scientific theory, it was actually the insight that measurements are far more powerful than intuition. He did not just need to recognize the existence of heat loss, but rather, its magnitude.

While the benchmark for steam is obviously 100 degrees centigrade, a number of variables such as the material containing the liquid, will affect the boiling point. This was key in his understanding that water would actually boil at a lower temperature in a vacuum, but the resulting steam would then degrade that vacuum. Watt's notebooks are filled with measurements as he tried to determine the volume of steam compared to water, how much steam was used on a single stroke of the engine, how much water was needed to then condense that steam, and so on. He actually came up with a very accurate calculation of the relationship between liquid and solid volumes of 1,849, drastically correcting Desaguliers' calculation of 14,000 (Hills 1989, p. 93). Watt himself then describe his true debt to science (cited in Fleming 1952, p. 4):

> *I mentioned it to my friend Dr. Black, who then explained to me his doctrine of latent heat… I thus stumbled upon one of the material facts by which that beautiful theory is supported… Although Dr. Black's theory of latent heat did not suggest my improvements on the steam engine… the correct modes of reasoning, and of making experiments of which he set me the example, certainly conduced very much to facilitate the progress of my inventions.*

What this theory meant for the steam engine is that after boiling a quart of water, the resulting steam will take up 1,849 times the space it did when it was liquid. Newcomen's engine injected some water into its sealed cylinder in order to create a vacuum from the condensed steam. After a year of exhaustive experimentation and measurement, Watt quantified the precise amount of water needed to condense the steam. These test showed why the Newcomen engine was so inefficient, since it was caught between fundamentally incompatible goals of using minimal water to condense the steam, but maximum water to ensure condensation. In other words, the cylinder had to be kept at 100^{o}C to avoid condensation, but also at 45^{o}C to avoid vaporization. In a testament to Britain's favorable environment to inventors in the latter half of the eighteenth century, Watt spent many years struggling with solving this paradox. He finally came up with his epiphany of a separate condenser, where steam would flow and could be cooled without cooling the main cylinder. This is the culmination of Watt's training, as actually building the separate condenser required his skilled hands honed by his apprenticeship in constructing brass compasses and quadrants.

Baconian (English) versus Cartesian (French) science

The two great philosophers who ushered in modern science in the early seventeenth century are often seen as proxies or prophets for the views of science and its role in serving social progress in their native countries. Francis Bacon's (English) vision was of scientists travelling the world collecting facts, until their accumulation reveals how nature works by induction. In the world of Rene Descartes, the (Cartesian) scientists should stay home and deduce the laws of nature by pure and rational logic and thought. While many English scientists, such as Faraday and Darwin were Baconians and many French, like Pascal and Laplace were Cartesians, the national distinction does not hold always up. In fact, the best science was a cross-fertilization of the two contrasting cultures. Even the president of the Royal Society, Isaac Newton was a Cartesian at heart, using its methods and mathematics in some of his theories.

Another stereotype placed on the two countries given their respective "fathers of modern science" is that England was unique in its pragmatic and experimental science, which was primarily geared towards commercial means. Whereas Cartesian France was stuck in an abstract and theoretical program that was government-driven with no aspirations for application to technology. This view not only contradicts Bacon's own preference for a state-sponsored science institution, but also his aversion to exploiting innovations for personal and not public gain. Furthermore, while most of its first members subscribed to Cartesian precepts, the French Académie des Sciences was never officially Cartesian rejecting doctrinal dogmatism and its members also invoked Bacon's example of Salomon's House (Hahn, 1971 p. 31). Lastly, while the Royal Society was far more Baconian than the French Académie, its fellows were all heavily influenced by a sort of Cartesian mechanical philosophy (Hunter 1989, p. 70).

Leaving the Baconian versus Cartesian debate aside, it is important to remember Mokyr's concept of the Industrial Enlightenment, where "useful knowledge would henceforth be judged by its intrinsic value, not by the nationality of its origin" (Mokyr, 2002, p. 54). Even if the science was better or more practical in one country or the other, it did not really matter as Western European scientists and engineers studied and copied each other. While the switch from Latin to vernacular languages provided access to technical and scientific writing to those without a classical education, it created a manageable obstacle for foreign exchange. Smeaton taught himself French in order to read the French theories on hydraulics. Watt also learned French, Italian and German in order read scientific literature, including Jacob Leupold's treatise on Papin's engine. Inventors did not always have to learn a foreign language to get access to overseas knowledge, since scientific and practical tracts were often translated. The French chemists were superior to their more practical British counterparts, prompting an English translation of Berthollet's *Art of Dyeing* (Keyser 1990, p. 225). There were also numerous personal contacts between the countries' scientific communities, as English scientists often visited France to pay homage and confer with their fellow experimental philosophers (Brockliss 1992, p. 79). Lastly, as described in the section on industrial espionage, the English Channel did not isolate useful knowledge and either spies or government diplomats would regularly acquire foreign technological information.

Resource Endowments

Demand for Energy

Alternative Energies: water and wind power

Energy is the lifeblood of civilization and those who maximize it by performing their tasks most efficiently are the most successful. Energy is used to do work, produce things, heat buildings, cook, and transport. For millennia, caloric energy fueled human muscle power that allowed us to hunt, gather and eventually work in the fields. Humans are a bit more efficient than animals at converting calories into work, utilizing roughly 18 percent compared to only 10 percent for a horse or ox. This is one of the reasons slavery or conscription was so prevalent in human history. However, if animals generally ate foods inedible for humans, their efficiency could be greater so that they could do the heavy lifting. Unfortunately, humans produce a pitiful amount of power, best illustrated at the local science museum by the bicycle or hand-driven ergometer that barely illuminates a connected light bulb. In addition, when poorly fed (and motivated) laborers are forced to perform work, they are even more inefficient, only producing half of what free laborers performing the same work (Derry and Williams 1960, p. 243).

Harnessing nature using water and wind technology is much more recent, but Egyptians were using waterwheels for irrigation and milling over 3,500 years ago. The Chinese had built waterwheels to operate iron-smelting bellows in the first century. Around the same time, but in Augustus' Rome, the engineer Vitruvius (whose writings on geometry and the human body inspired Da Vinci's "Vitruvian Man"), wrote that the machines are "rarely employed", which has the economic explanation that cheap slave labor was so prevalent in the Roman Empire (cited in Gies and Gies 1994, p. 35).

Wind power came to Europe likely during the eleventh century, but its use was limited by geography. In northern Europe, where rivers may freeze during the winters and the land is flat, they offered a comparative advantage, and were thus more common. It is important to note that although this connection between the physical environment and wind technology seems straightforward, geography does not always hold up as the causal factor in new technologies. For example, England was littered with water mills (the Domesday survey recorded over five thousand as early as 1086, or roughly one for every fifty households), while the similar climate of Ireland did not embrace the technology (Landes, 1998, p. 45).

Windmills and waterwheels provide a useful illustration of the gradual transition in the population that took place during Europe's Middle Ages. After the Dark Ages, watermills replaced hand mills in grinding grain into flour, but only when the population became dense enough to justify its high fixed cost. A builder needed to not only construct the mill, but also invest in diverting rivers and regulating the flow of water. Industries with such high fixed costs and economies of scale often exploit their market power and landlords in charge of watermills were no exception. Peasants often complained about the high tolls charged for their use. Watermills were later used for other purposes, such as pumping water, sawing wood and operating bellows to melt ore. Both wind and waterpower typically produced between 5 and 10 horsepower (HP), although the colossal “machine of Marly” in France delivered at least 75 HP, with a potential capacity of 124 HP (Forbes 1958, p. 148).

Limitations of Wind and Waterpower

Wind and water powered mills suffered from two fundamental shortcomings. First, they are site-specific and not necessarily in the same location where the work was needed. Secondly, the fixed cost nature of the technologies limited the incentives to improve them. Imagine your own motivation to drive economically if you were provided free gas. Water and wind technology saw gradual learning-by-doing advancements, which made them more powerful, but their operating expense largely remained the same.

In hindsight, it is clear that steam power liberated humanity from the vagaries of nature. In fact, almost one hundred years into the steam revolution, John Cooke (2010, p. 111) wrote a paper in 1795 to the Royal Irish Academy stating:

> *Water is seldom convenient; wind is a feeble and precarious agent; and muscular force is very expensive and very limited; but steam is free from each of these imperfections, and is superior to all in strength and duration.*

Nevertheless, in the context of the origin and early development of the steam engine, the limitations of other power sources, especially waterpower, did not play a significant role in most industries. In fact, it was not until after 1830 that steam power accounted for more than water and wind in Great Britain (Allen 2009, p. 173). The United States took even longer to substitute waterwheels and turbines with steam engines. There, it was not until 1880 when the balance shifted in favor of steam (Forbes 1958, p. 148).

So, in analyzing the effect that demand for energy had on the development of the steam engine in Britain and France, the industry where the technology was first applied should be primarily considered. While this could be considered cheating since history has already given its account of how steam power would be applied, it is precisely why economic history can provide more insights than pure economic theory or short-term statistical analysis. While steam power was later used to power mills, factories, boats and finally trains, the pattern of adoption is closely tied with the efficiency of the machines. The first steam engines only reached about 5 HP, which was about the same force produced by a waterwheel. Since there are no productivity differences between the two, the steam engine would only be purchased if it was more cost-effective than water or animal power. Desaguliers was the first to stress the economic case for steam power in reducing labor costs (Jacob 1997, p. 113). His own writing eloquently described the economics of the early steam engine (Desaguliers 1744, p. 464-465):

> *But where there is no water (for power) to be had, and coals are cheap, the Engine, now call’d the Fire-Engine, or the Engine to raise Water by Fire, is the best and most effectual. But it is especially of immense Service (so as to be now of general use) in the Coal-Works, where the Power of the Fire is made from the Refuse of the Coals, which would not otherwise be sold.*

Coal

For most of human history, wood was the fuel of choice. However, its use was limited to cooking food and heating living quarters. Then, almost nine thousand years ago, in the Near East, fire was used to liberate copper from its ore or mineral-bearing rock. Once the connection was made between heat and releasing the metals from rock, our ancestors began mining copper and working it to make tools. Other metals, such as tin and lead were discovered and eventually copper was mixed with tin to make bronze. This discovery ushered in the Bronze Age, when ancient civilizations built their empires on the production of relatively strong weapons and agricultural tools (not quite beating their swords into plowshares). As long as wood is relatively abundant and close at hand, it's heat was adequate for heating homes, cooking and even metallurgy, brick and glass making, pottery and brewing. But while wood is the original "renewable" fuel, it takes about fourteen years to mature. Moreover, just as a modern-day energy crisis would spur a search for alternative energy sources, Europe sought a new fuel during its "wood crisis" in the late twelfth century, as the continent fell many of its forests for construction and to open up enough farmland for the burgeoning population.

This was very apparent in London, where the price of firewood in London rose rapidly starting in the twelfth century. By 1230, England was forced to import most of its timber from Scandinavia, but that did not stop prices from increasing. In Surrey England, the price of a firewood faggot rose "by some 50 percent between the 1280s and the 1330s" (Galloway, Keene and Murphy, 1996, p. 449). The city and its industries turned their sights to coal. For space-heating, medieval England made use of "sea coal", which was a young coal filled with sulfuric impurities found in easy to reach seams along the River Tyne to the North Sea. The noxious rotten egg smelling smoke actually caused King Edward I to ban its use and it was not pure enough to generate enough heat to be used for working iron or glassmaking.

There is a debate between economic historians over whether the increases in wood prices were due to a timber shortage or from increased demand as the city of London grew. While that debate is inconsequential for this analysis, in an attempt to settle it, Robert Allen generated a dataset that illuminates the demand for coal in England. His graph shows the "real prices" (price divided by a general price index) of coal relative to wood in London from 1400 to 1800. Clearly, something happened to the price of wood from 1550 and one explanation is the exploding population with their corresponding demand for fuel. Indeed, London's population jumped from about 55,000 in 1520 to 200,000 in 1600, which was the same timeframe in which the price of wood exploded. Things just got worse and by 1650, the gap between coal and charcoal prices was so great that despite its foul smell and undesirable qualities for cooking, coal was in extensive use by that point. As Allen puts it, "the growth of the coal trade was the result of the growth of the capital – not of a general shortage of wood." Similar to the transition from water to steam power, the increased price of wood made investments in coal mining profitable. Indeed, coal production rose ten-fold in Britain from 227,000 tons in 1560 to 2,640,000 tons in eighteenth century, mostly from mines in Northumberland and Durham where the bulk was shipped to London (Hatcher 1993, p. 68).

The demand for coal energy preceded the steam engine and can be seen as a direct trigger for its invention (Allen 2011). Given the English domination of the coal industry in the seventeenth and eighteenth centuries, it seems obvious that the steam engine would be invented there. Some would attribute this as a geographic accident, since Britain was naturally blessed with an abundance of coal. But the transition from charcoal to coal is not easy and requires a considerable amount of modifying existing technologies in order to use it. We will soon see that many industries had to adapt to this new fuel, such as home building, brewing, glassmaking and iron smelting. The tremendous investments made in altering methods and uses, which became profitable only in Britain in light of the cost of wood, essentially locked it into a fortuitous path dependence on coal based solutions.

A geology professor, Richard Cowen (2016) at the University of California, Davis, has painstakingly described the process of coal mining during the middle ages. As coal production ramped up, its extraction became more cumbersome and hazardous. It required digging, usually into a hilltop, by rotating a large bore auger using men or tethered mules walking in circles. Then, miners would use picks to carve the coal from seams and cart it up to the entrance. Miners became skilled in “hewing” large lumps of coal, which were more valuable for their transport and burning quality. As the coalmines went deeper, they faced new challenges, such as how to support the structure and roof of the galleries to prevent cave-ins. Thicker pillars meant more safety, but less profit. On the other hand, if the roof collapses, there was a total loss, so miners were supported in an economic sense. Another issue was ventilation since methane gas can pool in sealed areas of mines, which can kill unsuspecting miners either by asphyxiation or by an explosion as they used fire for illumination. In addition, the deeper the mine, the more likelihood that the mine will flood with water.

By the late seventeenth century, the deep coalmines in the Northeast were in crisis due to all the flooding. The ever-increasing demand for coal in Britain was putting increasing pressure on contemporary technologies. The English were either unaware of or unsuccessfully tried to use the German flat-rod engine (*Stangenkunst*) to drain the mines, but it was also dependent on some sort of external power. Animal power was the preferred method of pumping, but that was becoming painfully expensive to coal masters (Harris 1992, p. 4-5). It was in this atmosphere that Thomas Savery marketed his “Miner’s Friend”, which served both as a water pump and a method of ventilation. In fact, three-quarters of patents granted in England prior to 1700 were mining innovations (Wallace 1982, p. 33).

The mere presence of coal is not sufficient to initiate a coal mining industry. France had an expansive coalfield in the north (crossing into Belgium), as well as its central Loire coal mining basin. While the reserves of these areas paled in comparison to Northeastern Britain, their existence shows that something more than just the natural resource needs to be present. The population in Paris experienced a significant boom after the losses from the Wars of Religion, doubling from 210,000 in 1594 to 420,000 in 1634, after the spectacular recovery under the converted King Henry IV and his Edict of Nantes. Shouldn’t the Parisian population boom have also spurred increased wood/charcoal prices that would lead France to develop its coalmines? The answer brings us back to natural resources and prices.

Paris did face an increase in the price of firewood during the 1600s, but not nearly to the degree that London experienced. Coal prices in Paris were not thoroughly recorded until 1840, nevertheless Robert Allen (2009, p. 101) diligently compiled average real energy prices in Europe. The data quality can be confirmed by comparing coal prices in Paris with Antwerp.

Antwerp serves as a decent proxy given its supply sources (Northeast England and Liege) would make transportation costs quite similar to Paris. The price difference between charcoal and coal in Antwerp was similar to London (charcoal priced at least double of coal), which was enough to induce consumers to buy coal, with its noxious smoke. In Paris, charcoal was actually cheaper than coal well into the late 1700s, long after the invention of the steam engine (Allen 2009, p. 98).

Table 1 - Energy prices in Europe (1600 to 1800). Allen (2009)

	1600	1650	1700	1750	1800
London, coal	2.63	3.56	3.93	3.96	3.84
London, charcoal	5.08	10.21	11.12	10.08	
Northeast UK, coal	0.60	0.48	0.54	0.75	
Paris, coal	5.50	5.39	6.95	6.65	
Antwerp, coal	4.92	6.41	7.61	6.60	5.51
Antwerp, charcoal	9.96	10.49	12.61	13.94	12.31

The great coal-bent historian of the Industrial Revolution, John Nef (1932, p. 222-223) quoted a Frenchman named Ticquet who sent a letter from England to Paris in 1738 writing, "coal is one of the great sources of richness and abundance in England; I regard it as the soul of the English manufactures". While Britain was blessed with an abundance of coal, France was equally blessed with forests, which kept the price of firewood relatively stable, despite the population increase. This inhibited the need for a coal mining industry in France until the immense industrial demand using coal-powered steam engines well into the industrial revolution in the mid-1800s (Lamb 1977, p. 255). Even then, with tariffs on Belgian coal to provide a buffer for domestic producers, and a vast network of canals and rails, French coal was double the price of Belgian coal at the pit head (Milward and Saul 1973, p. 333).

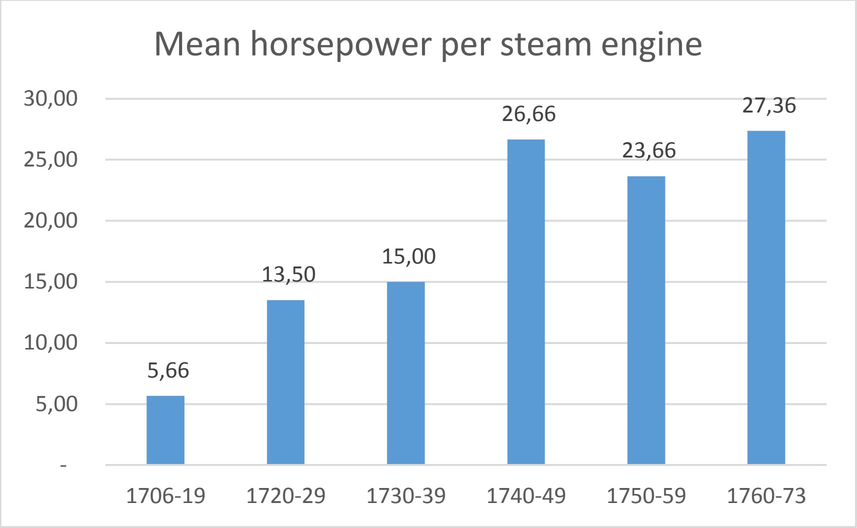
Figure 12 - "A Newcomen Engine ca. 1700" (Tobey 1961)

The fates of Britain and France diverged in the seventeenth century due their differing abundance in coal versus timber. While the demand for heat energy was similar given their parallel population booms, the relative supply of the energy sources determined their vastly different prices in the two countries. It was Britain's fuel trajectory that motivated its coal mining industry in the north and west peripheries of England. Even though the Northeastern mines were relatively close to the water, the transportation costs of getting piles of coal at the pithead to the harbor were extreme. Wains, which are large carts that could carry close to a ton, were used to transport coal to the water. Remember that one trip only carried a ton, so thousands of tons would require that many return trips. Imagine the demands on the road, the pastures and care needed for the horses and oxen. The great mines around the Tyne needed to load its coal first onto specially built smaller "keels", which then needed to be rowed to the sea before the coal was loaded onto larger ships bound for London or Europe. Finally, once their destination harbor was reached, the process started all over again to get the coal to its buyers (Wright 2016, p. 1). Waggonways (the predecessor to railway) and canals eased the transportation burden, but not until well after the invention of the steam engine.

The high transportation costs meant that coal was extremely cheap at its pithead, which is precisely why Newcomen's first steam engine was used to drain a coalmine in Dudley in 1712. The machines were terribly inefficient, using only one percent of the heat generated by the tremendous amounts of fuel they burnt (Thurston 1878, p. 464-470). They were only cost-effective when the fuel was practically free, like at a coal mine where the bits that could not be sold could nonetheless be burned. The operation of the engine, which worked in a reciprocating motion, was especially suited to pumping mines. There was no other feasible application of those first steam engines. But this was by design, as the object of the machine was to drain mines. Therefore, the steam engine solved a uniquely British problem using a uniquely British resource. In the absence of the steam engine to pump water out of mines, the cost of coal surely would have increased. Not only was animal feed costly, but horses were not as effective in powering the water pumps. A study was made in 1752 comparing the cost of horses versus a steam engine in pumping water from a 72 meters deep coalmine in northeast England. Horses worked two at a time in three-hour shifts lifting about 300,000 liters of water per day for 24 shillings. The steam engine handily beat the horses only costing 20 shillings a day and pumping *four times* as much water (Pacey, 1992, p. 159).

Market Size: Mining

If we again limit our scope to the steam engine's initial markets from the first Newcomen engine in 1706 to the first commercial Watt engine in 1773, it would be miraculous if it was invented anywhere outside of Britain. The diffusion of engines during this time is hotly debated as the commonly used Kanefskey database contains omissions and discrepancies when compared to secondary literature (Kanefskey and Robey 1980). Complicating matters, many engines fell into disuse or were moved from one location to another. Harry Kitsikopoulos (2008) uses a novel approach in dealing the shortcomings of merely counting engines by calculating the diffusion of horsepower in use during this period. The database provides a number of insights, including the growth in the horsepower during the almost seventy years of gradual improvements.



Using this dataset to distinguish the diffusion by sector shows that about 9 out of 10 engines were used in the mining industry. The rest of the engines went to ironworks or waterworks and mostly after the average horsepower exceeded 20. The regional diffusion within England also reflects the invention's dominate use in coal mining.

Table 2 - Newcomen steam engine diffusion in British counties

1718		1742		1773	
Durham	24.9 (21%)	Northumberland	297.8 (13.5%)	Northumberland	2,254.5 (17.3%)
Staffordshire	18.2 (15.3%)	Warwickshire	289.6 (13.1%)	Durham	1,542.3 (11.8%)
Cornwall	16.9 (14.2%)	Durham	256.1 (11.6%)	Cornwall	1,473.5 (11.3%)

As half of Britain's coal was mined in Northumberland and Durham, it is no surprise that these two counties played a leading role in adopting the steam engine. Cornwall, according to both Savery and Newcomen, was to be their largest market as it was there the mining industry was in crisis and desperately needed a solution to its flooding problems. Cornwall, on the southwestern tip of England, is filled with copper and tin deposits. However, its geography made those minerals, which were in high demand by 1700, extremely difficult to mine. Cornish miners had to dig individual shafts downwards (in contrast to the horizontal tunnels in coalmines), which were the deepest holes in Britain. Their daily commute to work included travelling up and down as much as 800 feet, either by ladder or a mule powered rope (Leifchild 1968, p. 139-142).

Because Cornwall is on the sea, the shafts would continually flood, making pumping or drainage tunnels an absolute necessity to keep the mines running. A woman traveler by the name of Celia Fiennes wrote of the mines during her tour of the West Country in 1695: “They even work on Lord’s day to keep the mines drained – one thousand men and boys working on drainage of twenty mines”. She also remarked that she saw “a hundred mines, some of which were at work, others that were lost by waters overwhelming them” (Burke 1978, p. 171). The first machines proved to be a false hope for both the mining industry and Newcomen, given the high cost of coal in Cornwall (both due to a duty on sea-borne coal as well as the tremendous shipping costs of mule carriage from the Cornish ports to the mines). By 1727, there were only five Newcomen engines working in Cornwall and the technology was not attempted again until critical efficiency gains in the 1770s (Leifchild 1968, p. 183).

As the diffusion of the first steam engines was determined by the location of coalmines, one would expect to find them installed in France and Belgium. Indeed, there were a few Newcomen engines in France, but their use was not widespread (Ballot 1978, p. 384-387). This is apparent since the French secret agent, Jars, provided his government with a very careful description of a Newcomen pump in 1765 (Szostak 1991, p. 162). The French did use one machine installed by two Englishmen to pump water from the Seine to the city of Paris. A similar scheme was also introduced on the Thames in London.

The more efficient Watt engine was introduced to France in 1776 by Jacques-Constantin Périer, who had acquired the right to assemble them to work in the Parisian waterworks. He prospered in the 1780s as his machine shop near Paris built numerous steam engines for the Anzin coal mine, ironworks at Le Creusot and various waterworks, but its adoption was slow and the business struggled in the 1790s (Payen 1969, p. 99-166). By 1810, Périer estimated about 200 steam engines in France, almost exclusively in coalmines, compared to 5,000 total in England (Henderson 1961, p. 45). Harris (1992, p. 211) presumes that Périer included Belgium in those numbers as he was only able to count 70 engines by 1800. Even long after British industry began using the steam engine to drive machinery, there were only 15 French factories that had steam engines (Fohlen, 1970 p. 142). Again, this is due to the excessive cost of coal in the industrial areas of France.

While engines developed after Watt made tremendous fuel economy improvements, the cost of coal remained 45% of the total costs (with capital another 45% and labor 10%). A steam engine itself was extremely difficult to transport, costing almost 10% of the price of the machine (Price, 1981, pg. 19). A Commission of Inquiry reported that the lack of canals and roads, which made coal transport so expensive, was the principal reason the steam engine was not used in France (Fohlen, 1970, pg. 141). While reliable coal prices prior to 1800 are unavailable, in 1831, a bundle mined at the pithead at Rive de Gier (in the Loire coal mining basin) cost just 15 francs, yet 53 francs at Mulhouse, France's leading textile center just 400 kilometers away in Alsace (Price 1981, p. 119). Steam engines were almost exclusively limited to mining areas in France, until transportation improvements, such as canals or railways, eased the cost of coal. One such example is the Alsace cotton industry, which only adopted steam technology after the 1833 Rhone-Rhine canal was built, which allowed easy access to the coal of the Loire (Fohlen, 1970, p. 144).

The early industries in Britain and France were not located in a prime position close to the coalmines. England saw the rise of its cities, which set the stage for a large-scale factory system. France's industrial concentration grew out of its medieval commercial centers. The promise of steam technology was that factories could be located anywhere, preferably close to coal, transportation, labor and markets. France was at an extreme disadvantage in this regard, since it had labor, transportation and markets built up around water technologies. Building roads and canals and the natural development of cities inevitably entails significant sunk costs. Even if the state determined that the potential opportunities were great enough to justify abandoning existing industries and cities, it would be hard-pressed to convince its inhabitants to relocate merely to get closer to a cheaper source of coal. A study of France's historical geography by Hugh Clout (1977, p. 475) found that the location of its coalfields "were surprisingly unattractive for key industrial sectors, such as textiles and metallurgy". Another observer reasoned that a better transportation network for coal was not developed earlier because "France neither needed nor found it possible to develop the resources quickly" (Dunham 1955, p. 85).

Steam adoption in French industry did not occur until the efficiency of the machines made them cost-effective or the transportation network was improved, decreasing the cost of coal in the industrial centers. In the meantime, the French showed their ingenuity in water technology, as late as 1844, getting 21,710 horsepower from hydraulic engines, over the 5,982 horsepower that would have been realized by a steam engine. The first steam engines used in French manufacturing were actually to supplement existing water technology, since the streams were so crowded there was no room for another waterwheel (Landes, 1973, p. 182).

Britain had the first mover advantage since its northeast coalfield was the chief supplier of household coal. Even into the 1840s, British homes were consuming two-thirds of British coal output and a shocking 40 percent of the world's (Rosen 2010, p. 89). In that environment of intense consumer demand, mine owners and industrial speculators began financing investments in transportation that would ease the burden of getting coal from the mines to the cities. An example is the canal built between a Duke's colliery at Worsley and the rapidly growing town of Manchester in 1761. It was reported that within weeks of the canal's opening, the price of coal in Manchester was cut in half. At the dawn of the railway age, Britain had successfully linked most of its coalfields, industrial centers and ports with over four thousand miles of navigable waterways, rivers and canals (Bagwell and Lyth 2002, p. 8-9).

It should be noted that an early lead in technology can sometimes be a disadvantage, since followers can avoid the tedious route and can easily follow a more direct and optimal path. In fact, when France did widely adopt steam-engine technology starting in the 1820s, it was the more fuel efficient and cutting-edge Woolf design that became the standard. In fact, it is in this era when French engineers declared independence from the British design standards as they began to successfully adapt a design that was favorable to local conditions in France. Britain put up with their coal-guzzling Boulton and Watt low-pressure engines for many decades after their technology was outdated. It was not until the 1840s that English factories invested in the high-pressure engines of the time (von Tunzelmann 1978, p. 281).

Supply of Inputs

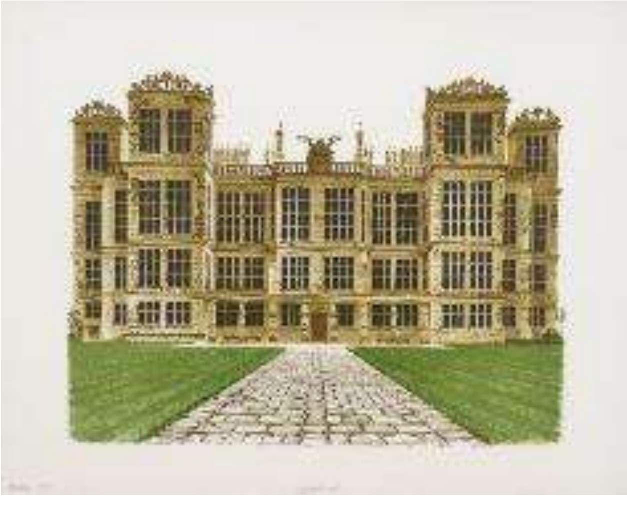
Without cheap coal, the steam engine would have remained a theoretical experiment with no practical application. Does that mean given access to cheap coal, the steam engine would have had an equal chance being invented in France? When we examine the parts and the metal working skills, which were used in the first iterations of the steam engine, we again find the British exceptionally fortunate. As Landes (1969, p. 182) notes:

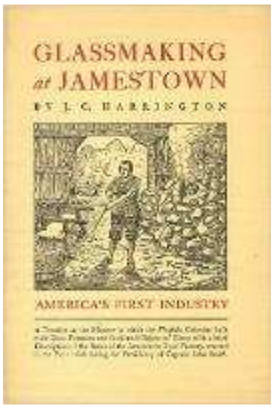
> *In the eighteenth century, almost all of the continental steam-engines came from England: if it was hard for British metal-workers to achieve the precision required, it was almost impossible for French or German craftsmen. Not only did they lack the manipulative skills, but their materials were inadequate to the task – to soft or brittle and uneven in quality.*

Coke and Cast Iron

It is one thing to build a prototype or model of a steam engine, but get the same precision and parts necessary for "mass" production is a completely different ball game. Newcomen first experienced the headache of finding a metal cheaper than brass to make the critical part of the engine, its cylinder. Explaining the solution to Newcomen's cylinder problem requires a slight detour, but one which provides additional insight in the differences between the inventive capacities in England versus France.

Going back to the population and property boom in London during the 16th century with its timber crisis. Wood was not only being used to build and heat houses, glass makers were also rapidly cutting down the forests to make charcoal for their furnaces. Glass windows were the fashion of the day, first among the rich and eventually common in most homes by the 17th century. This is dramatically exemplified in Hardwick Hall, said to be "more glass than wall".





England was desperate for alternative raw materials to make glass. One scheme to satisfy the demand was to build glass factories on the new continent (America). Indeed, together with my ancestor on the boat to Jamestown Virginia in 1607, were eight German and Polish glassmakers (as there were few skilled English craftsmen), who had vast forests and sand essentially free at hand. But, the realities of building an industry which required travel in a leaky boat for 4,000 miles in a harsh landscape surrounded by sometimes hostile natives, was too much and the idea died by 1610, along with 80-90% of the original settlers (Harrington 1972). The craziness of the scheme shows how desperate the English actually were.

Another scheme was devised in 1612 by Sir Edward Zouche, a crafty courtier with an eye for a fast buck, convinced King James I (after paying him 1,000 pounds) to grant him and his partners a monopoly on their newly invented coal furnace. The reverberatory furnace, originally described by an Italian Renaissance metallurgist, attempted to prevent the impure coal soot from contaminating the glass by using underground pipes to draw in fresh air. One of Zouche's colleagues, Sir Robert Mansell (who was coincidently in charge of the Jamestown operation and not coincidentally an owner of a few coalmines), bought the whole stake in the coal furnace monopoly. Even though the quality and price of Mansell's glass was inferior to his competitors, Mansell was able to convince the king (amidst rumors of bribery) to outlaw all fuels but coal in glassmaking. The monopoly was a constant subject of controversy and by 1622, Mansell was taken to court by his competitors. On the jury was another enterprising fellow, Viscount Grandison, who after hearing about Mansell's wealth, decided to get into the coal furnace business using it to smelt lead near Bristol (Burke 1978, p. 168).

This minor historical detour not only sets the stage for the next hero of British industry, but also illustrates how the first patents or monopolies in England were abused by the Royalty and the rich merchants (more to come on that topic). It is also important to note that these monopolies were eventually expired or were cancelled after the English Revolution, when merchants lost much of their influence over policymaking. Parliament started encouraging capitalist entrepreneurship in exploiting human and natural resources. The Mines Royal Act of 1689 ended the monopoly on brass making and the English port town of Bristol was especially suited to produce brass. Brass was made by combining Calamine (zinc) with copper, both of which were abundantly available close to Bristol (Gentle and Field 1975, p. 25). It was in this environment that an ambitious young Quaker[14] named Abraham Darby showed up.

Abraham Darby

When a twenty-one year-old Darby arrived Bristol, he had already been educated as an apprentice "malter" of beer and whiskey for seven years. He was also embraced by the city's small, but tight knit group of industrially minded Quakers, who welcomed him as one of the principals of the Bristol Brass Works Company. The firm attempted to produce household utensils, like brass cups and spoons, but the Netherlands held a near monopoly in the industry

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[14] This explains why there are no painting made of the man.

with their secret low-cost method for casting them. Darby travelled across the channel and used espionage to learn the industrial techniques of Dutch casting. Casting in clay made the process painstakingly time-consuming, but the Dutch secret he discovered was to cast in sand, which allowed for standardized, repeat production. He recruited a number of skilled Catholic workers, who were guaranteed freedom of worship in Bristol, and taught the Darby how to beat the cold brass into shapes using water-powered hammers. He quickly patented his process, which made the casting of ware "cheaper than they can by the way commonly used" (Smiles 1864, p. 110).

Darby realized that his new method might also work for the far cheaper material of iron. While he worked on casting iron in sand molds with a fellow Quaker, John Thomas, their experiments were carried out in the utmost secrecy, where even the key holes to the building were covered to prevent the same espionage Darby himself had used in the Netherlands. Darby and the others' experience in casting brass into complicated shapes provided invaluable as they synthesized those techniques with those of iron founders to make iron pots that were about a third lighter than their competitors (Trinder 1974, p. 14).

While Darby's experiments with casting iron required large capital investments, the Brass Company refused to advance more money and he moved to Coalbrookdale in 1709, where he leased an unused iron furnace and forges. Darby's luck was unparalleled as his competitive advantage and patent allowed him to succeed beyond expectations. In fact, his success even exceeded the capacity of the local forests to supply him with enough charcoal to keep the furnaces going (King 2011, p. 133).

Similar to glass making and heating homes, a charcoal shortage was nothing new to Britain and often disrupted iron production. Interestingly, Darby's great-uncle, the 5th Baron Dudley, used an existing patent and in 1619, took out his own patent for making iron with pit coal. His life would be a hit reality television series today; after a strategic marriage at the age of 14, he struggled his whole life with paying off debts inherited from his father and supporting his official family of five children as well as his illegitimate family of 12 children from his longtime mistress (Clark and Dudley 1881, p. 4).

Baron Dudley's method for melting iron with coal remains a mystery, but his unfortunately named illegitimate son Dud Dudley inherited his father's drive and one of the furnaces used in their ironworks. Later in life, after surviving the English Civil War when he escaped capture as a Royalist officer, and his subsequent life as a fugitive playing a doctor, he wrote a self-aggrandizing memoir called Dud Dudley's Metallum Martis (1665). It was somewhat of an investment prospectus, in which he bragged about how much high-quality iron he produced with little or no charcoal. He likely never did succeed though, since chemical analysis later showed that the coal he used was not suitable as a raw material for coke (Ashton 1951, p. xi-xii). Despite conspiracy theories claiming that Darby inherited the Dudley knowledge of smelting iron with pit coal, the truth is that Darby's luck and prior experience as a malter was just what was needed to crack the code (King 2001, p. 41).

We should be celebrating Darby's fortune at this point, as it served to solve Newcomen's problem of mass-producing the steam engine as well as providing the iron and eventual steel backbone of the industrial revolution. Coalbrookdale, as the name suggests, is in one of those areas in England rich in pit coal. As Dudley likely experienced, using coal to smelt iron left it brittle and inferior due to the coal's sulfur being mixed with the molten iron. It was that same sulfur that caused roasting barley malt with coal to make beer that tasted like rotten eggs. Just as Darby learned as an apprentice malter, one could use coke to minimize the problem of contamination.

Coke is basically coal baked at high temperatures without air contact, which burns off the sulfur and leaves a cleaner fuel. However, it takes a special kind of bituminous coal to create cakes that can successfully smelt iron. While Dudley's coal was unsuitable, in a fortunate coincidence for Darby, Coalbrookdale coal was unusually low in sulfur and was especially fit for the job (Ferguson 1967b, p. 265). The coke was not only much cheaper than charcoal, but it produced significantly more heat, which is needed to cast iron (pouring molten iron into molds rather than hammering a cooler iron into shape). His cheap alternative to brass arrived just in time for Thomas Newcomen to become his first major customer, ordering a large number of cast iron cylinders and boilers for his steam engines (Ashton 1951, p. 41).

Réaumur

Another figure in the story of cast iron, serves to introduce the comparison with France, and deserves special mention. René Antoine de Réaumur was a brilliant gentleman scientist who was educated at finest schools in France and became one of the first members of the French Académie at age 24. His Wikipedia entry makes him seem like the A.D.D. poster child of scientists conducting research in metallurgy, egg incubation, temperature measurement, insect behavior and motion, lost limb regeneration and much more (René Antoine Ferchault De Réaumur 2016). He served King Louis XIV in compiling a description of France's natural resources and industry. He strongly supported the government's active engagement in funding science (or "useful knowledge" as they called it), believing the investments would pay off many times over, while he himself declined the huge pension granted for his discoveries.

Ironworkers struggled with matching the different grades of iron ore to their unique process accommodations. Smelting iron is a lot like cooking where basic ingredients can vary greatly in quality. Prior to modern-day chemical analysis, they roughly categorized the iron by color. For example, gray iron contains graphite carbon (the same stuff as in pencils) which is well suited as a casting material, while white iron is combined with sulfur and other elements that make it a brittle substance (Oberle 2013, p.157-158). Réaumur brought a scientific view to the classification at the same time that Darby's practical experience was independently used to classify various forms of iron into ten grades, which is still used today to choose the optimal raw material (Usher 1954, p. 374). Réaumur also performed experimental research inventing the cupola furnace and developing malleable iron (René Antoine Ferchault De Réaumur 2016).

Réaumur contrasted with Darby is a perfect example of the very different natures of science and entrepreneurship in France and Britain. He was devoted to science and pure knowledge in the service of his nation. Britain also had scientists like this (think Robert Boyle), who cared mostly about scientific glory, but she also had thousands of entrepreneurs like Darby, who sought to commercialize on their practical discoveries. Both the pure and applied knowledge approaches ended up with similar breakthroughs, but something was missing in France that prevent it from exploiting the technology. Even by 1780, when a new more efficient coke blast furnace was introduced, the French still did not use it.

Many historians, and even U.S. politicians, use France's inability to adopt the new technology as an example to question the quality of French entrepreneurship under a high-tax monarchy system (Crouzet 1990, p. 29; Harris 1992, p.9). This is where it is easy to confuse causation with correlation by equating all the factors in the British model as causal simply because England gave birth to the Industrial Revolution. While English society was more capitalist with a focus on the pursuit of individual gain than "easy-going" France, it is actually coal and energy costs, which best explain why the French were so slow in adopting the new technology. In 1780, when coal was still quite expensive in France, the coke-powered blast furnace was not profitable. However, by 1850 the tipping point when British engineers had improved the technology to the point where coke smelting was cheaper than using charcoal, France quickly jumped on the latest blast furnace technology (Landes 1969, p. 221).

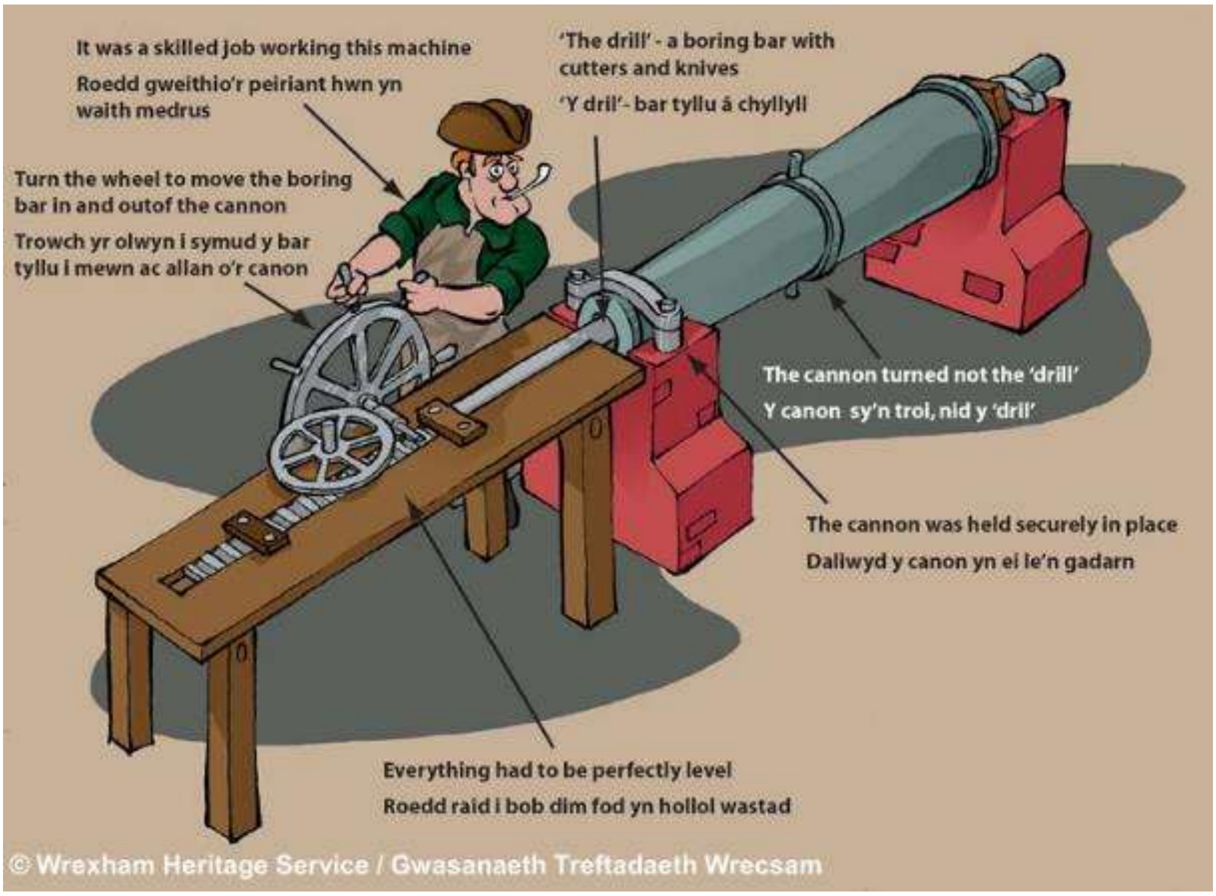
Robert Allen (2009, p. 149) notes, "it is ironic that the success of Britain's engineers in perfecting that technology destroyed the country's competitive advantage". This is precisely why sometimes lagging behind can be an advantage. Britain expended tremendous resources in the invention and development of steam technology, while the continent was able to "merely" emulate those technologies once all the kinks were worked out. The industrialization gap between Britain and her continental competitors (France, Belgium and Germany) essentially closed in the late nineteenth century, once those techniques became profitable to adopt outside of Britain.

John "Iron-Mad" Wilkinson

James Watt and Matthew Boulton were like the Steve Jobs and Steve Wozniak of their day as they combined their unique talents and capabilities to create a relentless partnership. While Boulton was working on securing a strong patent, Watt worked furiously on a flagship engine, which would be used to advertise the machine in a public demonstration. The engine not only had to be powerful and economical, but downright reliable. And while Watt worked with Boulton's team of craftsmen to create the finer parts of the engine, he was dependent on outside expertise for the large iron cylinders. He tried Darby's Coalbrookdale works as well as his former partner Roebuck's ironworks, but was regularly disappointed with their quality calling them "unsound and totally useless" (Ashton 1951, p. 63). He found himself stuffing soaked rags in the gaps between the pistons and cylinders to prevent steam from leaking out. The pistons needed a perfect fit to avoid friction or wobbling around and leaking air. While Newcomen's problem of mass-producing his engines at a reasonable cost required the concurrent innovation of smelting and casting iron, Watt faced a bigger problem. If he did not find someone who could cut the bore of a cylinder in the precise shape of its piston, he would not be able to produce any reliable machines, regardless of cost.

This is where we meet another religious nonconformist innovator, John Wilkinson, whose father was a master ironworker who acquired one of the Darby family's foundries. While the pacifist Quaker Darbys rejected military contracts, the Presbyterian Wilkinsons became an ideal supplier to the Office of Ordnance. John devoted his life to iron, earning his nickname as he built almost everything around him from iron, including an iron pulpit for his church and even several iron coffins for his burial. Twice married into wealth, he used his wives' dowries and inheritance money to establish and later outright purchase his own works, the New Willey Company (Dawson 2011, p. 1-2).

Wilkinson's military ties asked him to solve a problem artillery regiments were having with exploding cannons. While the shape of a cannon was quite simple, casting an iron tube often left invisible imperfections that could not take the stress when gunpowder was ignited to target the iron ball at the enemy. The common solution was to cast a solid cylinder of iron and then bore a hole into it, but traditional drilling did not make a perfect hole. His genius insight was to drill a pilot hole into a spinning cannon, but then he used a stationary drill that could advance the drill with extreme accuracy (Burke 1978, p. 175). While his patented innovation was intended to be used for military purposes, similar to radar, penicillin, and the internet, it was repurposed into something that benefited all of humanity.



This was the invention that James Watt had waited twelve long years for - a nearly perfect cylinder. Immediately, Boulton and Watt successfully used Wilkinson's cylinder in their first commercial engine and he was given an exclusive contract. Again, we see the development of the steam engine halted due to inadequate parts, only to be solved by other uniquely British innovations, which also sprung up due to England's switch to coal fuel (Gilbert 1958, p. 421). In the 60+ years from Newcomen's steam engine to Watt's celebrated innovation improving its efficiency, there were no relevant scientific discoveries. While Watt's genius is unquestionable, it was likely the advancements made in iron technology that explain the timing of his innovation.

Wilkinson was also a strong believer in steam technology and realized that as it grew, so did the market in symmetrically bored cylinders, for which he possessed a monopoly patent. He brought Watt engines into his own iron works to power his bellows as well as the forge's stamping hammers and presses. He urged Boulton and Watt to expand their horizons from mining to the larger market of driving machinery in ironworks using rotary engines. Wilkinson's passion for Watt's engines made him very wealthy as he invested in industries where he saw innovations paying off, such as copper mines in Cornwall that could now use the more fuel-efficient Watt engines (Dawson 2011, p. 104-124).

Although this is not the last time we will hear about Wilkinson and his business, it is an ideal juncture to note that the last feat in his life was to take up with one of his servant girls at the age of 77, with whom he had his sole three children. Even though he declared them legitimate, they lost his wealth after his passing as his iron empire fell apart due to a nasty legal dispute over his will (Crouzet 1985, p. 134). While he predicted he would reappear at his famous ironworks seven years after his death and several thousand people actually gathered there ready to witness the second coming of "Iron Mad" Wilkinson, resurrection was beyond his abilities (Weightman 2007, p. 36).

Lag time in innovation

The 80-year interval between the invention of the steam engine and its first major innovation by James Watt highlights the concepts of economic feasibility versus technical feasibility. It also explains the lag time between the first conceptual drawings of a steam engine and its invention. This section has highlighted that first steam engines were only economically feasible where the price of fuel was cheap enough to warrant their use in draining mines. It also emphasizes the limits to further innovation that would improve efficiency until air and watertight parts could be created which were tough enough to withstand the steam pressure. This obstacle was not overcome until developments in iron technology could be applied to producing immensely strong boilers and cylinders. John Enos (1962, p. 299-321) has studied other case histories to identify factors involved in the rate of innovation. A common thread is the reliance on other major breakthroughs. Developments in the long history of the steam engine were continually preceded by advances in metal-making techniques that could make high-quality boilers and cylinders a reality.

An eloquent historical materialist[15] explanation for the timing and location of the steam engine's invention and early innovation was provided by Karl Marx (1859/1928, pp. 12-13) in his introduction to *A Contribution to the Critique of Political Economy*:

> *Mankind thus inevitably sets itself only such tasks as it is able to solve, since closer examination will always show that the problem itself arises only when the material conditions for its solution are already present or at least in the course of formation.*

The economic explanation that a change in the relative factor prices will spur invention that is directed at minimizing the use of the relatively expensive factor is powerful in the context of the development of the advanced economies. However, it suffers in its inability to explain why

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[15] Historical materialism will appear again when investigating the role of science in directing invention as well as the cultural and political institutions in Britain and France.

underdeveloped economies, with abundant labor supplies but scarce capital, do not develop capital-saving technologies[16]. One possible answer comes from the renowned expert on the economic history of technology, Nathan Rosenberg (1976, p. 148), who posits that there is a sequence starting with labor-saving innovations which are followed by a capital-saving "breaking-in" process that works out the early "bugs" in production or exploits economies of scale. He also emphasizes the feedback effects within economies noting that if underdeveloped countries lack a capital goods sector, they do not have the opportunity to develop technical skills and knowledge necessary for generating capital-saving technique. This underscores the precondition that a country has the required technical skills prior to a technological change.

Economic Institutions

Financing and Capital

Transforming a great idea into a marketable product can take many years and a lot of money, not only to sustain the inventor's livelihood, but also for the materials required to perform the research and development. An examiner in the U.S. Patent Office, Joseph Rossman (1931, p. 54) surveyed more than 700 patentees in order to better understand their motivations. The three biggest motivators with equal weight place on each were "love of inventing", "desire to improve" and "financial gain". The survey also found that the biggest hurdle for inventors to overcome was the lack of capital. While investors do not always need inventors, inventors need investors. Indeed, financing was another cruel reality in a long list of headaches suffered by the steam engine pioneers. This was perfectly illustrated in James Watt's journey from his first model funded from £1,000 borrowed from university friend, Joseph Black, to starting a company that manufactured steam engines.

Raising capital in Britain in 1765 was extremely difficult as it was still reeling from the aftermath of the South Sea Bubble of 1720. The South Seas Company was one of the first Ponzi schemes, as the company's only real asset was access to Spanish controlled ports. Its stock price grew ten-fold in less than a year as it promoted its own prosperity and the riches to be made through lavish parties and luxurious offices in London. Other such swindles were numerous, including the ingenious "undertaking of great advantage; but nobody to know what it is" (Economist 2008). The Company capitalized on the unfounded exuberance by lobbying Parliament to prevent competition. The Bubble Act (1720) required either a royal charter or an Act of Parliament to set up a corporation with stocks (Harris 1994, p. 610-612).

This meant that James Watt needed to find a venture capitalist, who would put up their own cash to fund the new technology in return for part of the profits. On paper, it seemed like John Roebuck and James Watt would be a great match. Roebuck, who was university educated in medicine and chemistry, made his living exploiting technological innovation in his various business, which included a successful iron works, a sulphuric acid plant and a coal mine that struggled with flooding that a Newcomen engine couldn't fix. Roebuck fancied himself as a scientist and was quickly sold on Watt's discovery that producing steam in a vacuum was much

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[16] This puzzle can be added to mystery of the "late" invention of the wheelbarrow, that surprisingly didn't make an appearance until thousands of years after the wheel and at least another thousand years to reach Europe after its first use in China.

more efficient than in air. He agreed to pay off Watt's debt as well as all future expenses in return for two-thirds of future profits. Their partnership wore thin as Watt grew increasingly frustrated with the quality of Roebuck's smiths, who could not produce a perfectly round cylinder. In a testament to his confidence in his idea, Watt worked as a surveyor of canals on the side to support his family, since Roebuck's deal did not include a salary (Dickinson 1936, p. 42-44).

Their partnership ceased as Roebuck's coalmine investment was literally underwater. Roebuck pleaded bankruptcy and testified that the steam engine had already eaten £3,000 and would require another £10,000 to make it commercially viable. Matthew Boulton, who was already friends with James Watt, saw the diamond in the rough and bought Roebuck's share in the steam engine. This would turn out to be a match made in heaven as Boulton, in a letter to Watt in 1769, professed his "love of you" and his "love of a money-getting ingenious project" (cited in Dickinson 1936, p. 52). Showing the advantage of this type of partnership, Boulton would provide useful suggestions for improving the engine based on his manufacturing experience, a modern workshop, and most valuable, his vision to supply engines "for all the World…".

A James Watt equivalent in France likely would not have sought private venture capital, but rather support from the mercantilist state. France also experienced strict government regulation on banking after the collapse of Law's Banque Royale in 1720 (Smith 2006, p. 22). The French dirigiste model was laid out by King Louis XIV's Minister of Finance, Jen-Baptiste Colbert, who sought to enrich France through commerce (Jacob 2006, p. 56). The government played a role in establishing new industries, subsidizing inventors and protecting successful industries. French financiers or merchants of the time were chiefly occupied with their own enterprises and would seldom expand outside their own realm. Therefore, an innovator in eighteenth century France would likely turn to the government for a loan or subsidy, as long as they could prove their worth to the French economy. There were many privileges granted by the state on entrepreneurs, "most often they were granted interest-free loans for their first plant, or even given workshops, or the construction of machines was paid for" (Hoselitz 1955, p. 301). Royal subsidies were often granted to entrepreneurs, even foreigners, who had knowledge that could modernize existing manufacturing. From the English Milne family who earned considerable wealth for introducing spinning technology to France, to the joint venture with the Wilkinsons at Le Creusot, the crown sought to subsidize and reward those who could imitate superior British methods (Weightman 2007, p. 10-21).

While James Watt required capital, it was oddly not a complicated affair in the eighteenth century as it is today for tech start-ups. Boulton once remarked, "all the great manufacturers that I have ever known have begun the world with very little capitals" (cited in Hamilton 1809/1967, p. 271). Indeed Crouzet's (1985, p. 148) study of Britain's entrepreneurs shows that over 70 percent of the 226 founders of large industrial undertakings had middle-class fathers dealing with commerce. Also, about half of them were involved in manufacturing themselves, as craftsmen or managers. Often, the capital needs for small artisan enterprises could be funded by their own earnings, as they would start small and plow profits back into the firm for expansion. The frugality of these industrial pioneers can be traced to the overrepresentation of nonconformist religions that emphasized hard work and thrift, even after they had amassed wealth (Crouzet 1990, p. 188). Enterprises in France also largely operated with their own capital or a local loan backed by a mortgage (Palmade 1972, p. 62). This was fortunate given the relatively rudimentary business structures that abounded in the unlimited liability environments of England and France.

Because the inventors of the eighteenth century rarely had access to financial institutions (there were some country banks that would lend), they would usually just raise the small amount of venture capital from informal networks of relatives or friends (Crouzet 1990, p. 191). Many mentioned in this study either married well or took in partners to raise capital. The case of Watt, although it had a happy ending, highlights the risk of partnerships given conflict or financial troubles of a partner. But then again, as Boulton and Watt illustrate, they can also serve as an advantage given the correct division of labor.

Comparing the disparate ways of mobilizing funds in state-dominated France versus the informal institutions in Britain shows their similarity. Both relied on personal connections and an exclusive network. Numerous studies have searched for a change in banking and interest rates after Britain’s Glorious Revolution (1688), often cited as the birth of parliamentary ascendancy and individual property rights. According to a number of economists, this is the turning point in British history when a favorable investment environment was created, fostering the Industrial Revolution (North and Weingast 1989; Acemoglu, Johnson and Robinson 2005; Greif 2006). However, Clark (1996) and Epstein (2000) were unable to find any structural improvement in investment conditions. In the end, a lack of capital was not a likely factor in preventing the invention of the steam engine in France. Barring private investment, the state would probably see the value of a steam engine in the mining industry, had factor endowments in France been similar to Britain.

Property Rights and Patents

Intellectual property rights can provide the necessary incentive for a potential inventor to deal with the inevitable sacrifices that accompany the brave act of invention, by allowing temporary monopoly profits from the sale of the creation. Many economists believe that profit opportunities and demand for innovation is the fundamental trigger of innovation (Acemoglu 2008, p. 416). John Stuart Mill (1848/1996, p. 41) was an early proponent of this view when he wrote the following in Principles of Political Economy:

> *The labor of Watt in contriving the steam engine was as essential a part of production as that of the mechanics who build or the engineers who work the instrument; and was undergone, no less than theirs, in the prospect of a remuneration from the producers.*

While property rights in general have been shown to provide the necessary environment for modern economic growth, Joel Mokyr (2009, p. 349) reminds us that “the kind of institutions that incentivize technological progress differ from those that support the growth of markets by protecting property rights”. A number of different schemes can be employed to stimulate would-be inventors and investors, but it was the patent institution that emerged as the dominant method for national governments. Douglass North (1981, p. 164-66) posited that England’s patent system was exactly what was needed to systemically incentivize inventors, by allowing them “to capture a larger share of the benefits of his invention”. Richard Sullivan (1989, p. 424-452) supported this view by noting that the number of patents filed in England started rising in the 1750s, which coincides with the traditional start of the Industrial Revolution. Going back to Francis Bacon and other anti-monopolists, as well as more recently, others have questioned the evidence linking patents to economic growth, despite their purpose of promoting invention and innovation (Levine and Boldrin 2008; Mokyr 2009). Before evaluating the use of patents in the development of the steam engine and whether it may have had implications for the England versus France question, a brief overview of the patent systems at the time in those countries is provided.

English vs French systems

Proponents of the view that patents triggered the industrial revolution applaud Britain for establishing the first patent system in the world (Dutton 1984). This is a bit of a misnomer, since the original meaning of patents were not to protect the rights of an inventor, but rather as a way for the monarch to grant a monopoly. As the British royalty was constrained by parliament in its ability to tax, patents became a powerful tool in rewarding friends and promoting commerce. It was in the last full-year of Queen Elizabeth’s reign 1602, when such schemes would be put to the test, oddly in a case on the monopoly of playing cards. Edward Coke (pronounced Cook) was the Attorney General of England representing the monopoly holder, Edward Darcy, a well-regarding courtier of the Queen. This was a peculiar pairing since Coke had often spoken out against monopolies due to their suppression of Britain’s artisans (Fisher 2011, p. 79). Defending Darcy meant, “Coke was trapped between his politics and his profession, and he twisted himself into a pretzel trying to reconcile the two” (Rosen 2010, p. 70). Despite his strained arguments and surely to his relief, Coke lost the case as the justice ruled that Darcy showed no improvement in the “mechanical trade of making cards”, and the patent barred others from doing so. This idea, that you actually had to earn patent protection by demonstrating a novel improvement, was the foundation of subsequent patent law. In fact, it was Coke himself who twenty years later drafted the first patent law protecting inventors, called the Statute on Monopolies.

Christine MacLeod (1988, p. 17) literally wrote the book on the early English patent system and noted that the 1624 statute forbade all forms of monopoly except to the “first and true inventor”. Yet seventy-five years later, Thomas Savery was granted patent number 356, implying less than six patents were awarded annually. For all of Coke’s desire to support the British “working-class” artisans, the British system was biased towards wealthy inventors and against those with modest resources or incremental innovators. It was a widespread view amongst the elites of the time that invention was the business of the wealthy and educated, therefore, there was no reason to make patent applications easy or affordable. Kahn and Sokoloff (2004, p. 396-398) have documented the defects of the British system prior to its reform in 1852. For example, patent fees were five to ten time annual per capita income and most applicants needed the help of a patent agent to overcome the bureaucracy of the London offices. For a patent to be granted, the invention had to be novel, which was difficult to determine given the difficulty in access patent specifications. In addition, “if part of an invention is found to be meritorious and part useless, the patent is likewise void”, but the definition of useful or meritorious was made by non-expert judges or juries (Kahn 2005, p. 35).

France was also eager to promote invention via state policies, but despite the differences with the English system, was no better at rewarding “middle class” inventors. While the cost of obtaining a patent was cheaper than in Britain, it was still quite high relative to the average income of the time. However, an inventor in France could choose between applying for a patent or a state granted title or pension in the form of a lump sum grant, interest-free loan, production subsidy, tax exemption or exclusive monopoly grants of a region or the whole kingdom. As a potential improvement on Britain’s judge and jury system, France would examine award applications by a qualified committee that would evaluate based on the benefits to the public (Kahn 2005, p. 40). For all its promise, this case-specific evaluation of new technologies fared just as poorly as the British patent system. Rewards could be arbitrary and sometimes based on noneconomic criteria where some applicants were not even inventors, but rather had court connections (McCloy, 1952, p.171). The evaluations of “deserving” inventions could be very expensive to conduct and the expert committees were not necessarily qualified to assess commercial value or public benefit (Kahn 2005, p. 40-41). The scientific community charged with judging inventions could have vested interests to protect. Harris (1998, p. 562) describes “a large cohort of the frustrated and aggrieved among inventors…who believed that their efforts had been seriously affected by theoretically biased, impractical Academicians” by the time of the Revolution, contributing to the closure of the *Académie* in 1793.

As with most things associated with the French Revolution, the new patent law appeared modern on paper, but was quite different in reality. For example, the decree of 1790 stated “every discovery or invention, in every type of industry, is the property of its creator; the law therefore guarantees him its full and entire enjoyment. Yet the cost for filing a patent remained exorbitant, and did not necessarily guarantee intellectual property right protection. Also, in classic mercantilist fashion, a patent holder lost privileges if they applied for an overseas patent for the same invention (Kahn and Sokoloff, 2004, p.397). Access to patents for inventors without political connections or financial resources remained elusive both before and after the Revolution.

The two foremost experts in eighteenth-century patents, Christine MacLeod (1988) and Liliane Hilaire-Perez (2000), have written complementary studies that suggest that both the French and the British patent systems provided about the same incentive to would be inventors during the century. Both countries shared the Enlightenment view that institutions should encourage technological innovation by awarding exclusive rights to its inventors. France did this through a formal state-run committee of scientists, while Britain left the assessment of the invention’s worth to the market (and the courts when necessary). Britain’s government limited itself to protecting property rights, while French inventors would be seen as civil servants by the state (Hilaire-Perez 2000, p. 72). Harkening back to the divergent scientific traditions, this would put typically Cartesian France squarely in a Baconian world where invention was to benefit the public over the inventor. In practice however, both countries suffered from the shortcomings inherent to their respective programs.

Early Steam Engine Patents

An examination of the patents and their effects on early steam engine development in Britain is actually illustrative of the mixed results that a patent system can have on inventive activity. As noted earlier, pure scientists objected to the idea of patenting their ideas. While speculating is always a futile exercise, especially regarding an event occurring over three hundred years ago, one cannot help to think what would be different had Denis Papin patented his first steam engine design in the 1690. Would it have blocked Thomas Savery from developing his ideas and building the first commercial version?

Savery's 1698 patent

We do know that Edward Somerset, Lord Marquis of Worcester, had been granted a ninety-nine year monopoly by Parliament in 1663, just a few months before he published the idea in *Century of Inventions*, but that didn't stop Savery from receiving his own patent thirty years later (Muirhead 1858, p. 115-116). The first historians of the steam engine, Desaguliers (1744, p. 464-465) and John Farey (1827, p. 109-111) disagree as to whether Savery plagiarized the Marquis' writings. It is also unclear how Savery managed to convince Parliament to grant him a patent in light of the British regulation that they only be awarded to the "first and true inventor". I suspect that the abundantly wealthy Marquis' son, the first Duke of Beaufort, was either unaware or uninterested in pursuing a dispute over one of the hundreds inventions concocted by his father. He clearly had other things on his mind since just a few months prior to Savery's patent application, the Duke's heir and son was killed in a coach accident. The Duke himself passed two years later (Seccombe 1897, p.245).

Newcomen's 1705 Agreement with Savery

The first example of a steam engine patent actually having an impact came when Thomas Newcomen agreed in 1705 to build his engines under Savery's 1698 patent. In fact, Savery's original 14-year patent was extended to 21 years in 1699 by an Act of Parliament called the "Fire Engine Act". The monopoly covered all engines that raised water by fire, which meant that even though Newcomen's engine was much more advanced and markedly different, he was forced to collaborate with Savery. Savery's patent became vested in a company which managed the licensing of Newcomen engines, charging as much as £420 per year to merely operate the engine (Oldroyd 2007, p. 14). While the proprietors of the company established after Savery's death made a fortune, Newcomen shared in the prosperity with his five out of eighty shares. In a 1722 lawsuit, Newcomen described his intentions for the invention to "turn his engines or part of them into cash" (cited in Rosen 2010, p. 61). While he did not live long enough to exploit the expiration of the Fire Engine Act in 1733, the former ironmonger and lay Baptist preacher fulfilled his dream, at least in part from a portion of the proceeds.

James Watt's 1769 Patent and Subsequent Fire-Engine Act of 1775

James Watt exemplifies both the struggles of protecting ones patent as well as abusing its monopoly to prevent innovative competition. Watt was a perfectionist and did not have a love of business, once admitting, "I would rather face a loaded cannon than settle an account or make a bargain" (cited in Scherer 1965 p. 173). Even though he felt his design was still quite beta (still undergoing extensive testing not production-ready for another 7 years), his original business partner, John Roebuck, was anxious to start making money. He insisted that Watt apply for a patent, which he was awarded after a 6-month process in 1769. The patent number 913 became one of the most famous in history as "a method of lessening the consumption of steam and fuel in fire-engines" (Muirhead 1858, Vol 3, p. 1-8). Unfortunately for Roebuck, the patent did not generate enough money to buy coal to boil a kettle of tea and he sold it on to Watt's second business partner.

Matthew Boulton realized that his potential profits were already disappearing since they were almost half way through the original patent without having sold one engine. Working with a patent agent, Boulton uses his political power and requested an Act of Parliament, again called the "Fire Engine Act", this one of 1775, which extended their patent for twenty-five years. The victory did not come easy, since Boulton and the Father of Conservatism, Edmund Burke had already butted heads over the rights of the American colonists (Lord 1966, p. 101-102). Boulton proved the more persuasive and the act was passed on the argument that the invention already required tremendous monetary investment and would take many more years before they could sell engines "at moderate prices". The Act not only sought to allow Watt "an adequate advantage to his labor and invention", but also "the highest utility to the publick" (Scherer 1965, p. 184). Boulton was able to convince Parliament that the engine would not be completed without the extension. It is unlikely that Boulton really would have canned his investment because he would only have eight years of patent protection versus twenty-five.

Patent: Incentive to Innovate or Rent-Seek?

The Fire Engine Act of 1775, which has been called "the most important single event in the Industrial Revolution" (Robinson 1964), is a reminder that even the most groundbreaking innovators possess a greedy desire to protect their advantage once it is acquired. Boulton and Watt mirrored the sentiments of the young Saint Augustine, who prayed for chastity and self-restraint, *sed noli modo* (but just not yet). For all Watt's innovation, they also displayed minor rent seeking behavior (lobbying for protections in order to earn income without providing benefits to society through wealth creation). But, this is the difficult balance of states that attempt to encourage technological innovation. It is a knife's edge between rent-seeking monopolies and rewarding successful inventors. In the long view of history, the patent likely stifled innovation for over a decade, which could be argued, is not a long time to wait for a revolution.

Watt may have paved the way for more efficient steam engines with his separate condenser, but the innovations that came (some immediately) after his patents expired deserve credit for becoming the driving force of the Industrial Revolution. It is noted that fuel efficiency of Watt's steam engine improved very little during his patent, but merely between 1810 and 1835, it increased by a factor of five (Boldrin and Levine 2008, p. 1). Improvements, including Trevithick and Woolf's high-pressure steam engines, were lying in wait for Watt's patent to expire to avoid the same fate as Jonathan Hornblower.

Hornblower followed his father and uncle, who were both Newcomen engine mechanics, into the family business to work with Boulton and Watt installing engines in Cornwall in the late 1770s. He came up with a "compound engine" (more than one cylinder) that drastically improved on Watt's engine, coordinating two separate cylinders using the pressure exhausted from one to drive the other. This not only increased output by a third, it also smoothed out the "dead spots" from when the piston reversed direction (Rosen 2010, p. 208). Unfortunately for Hornblower, he infringed on Watt's broad "separate condenser" patent and was sued by Boulton and Watt in 1796.

When Watt learned about Hornblower's machine, he took it as a personal betrayal calling him "ungrateful, idle, insolent". He also wrote a compelling case for patents as a response to Hornblower's "theft", which illustrates their complicated nature (cited in Stirk 2001, p. 481):

> *If patentees are to be regarded by the public, as … monopolists, and their patents considered as nuisances & encroachments on the natural liberties of his Majesty's other subjects, wou'd it not be just to make a law at once, taking away the power of granting patents for new inventions & by cutting off the hopes of ingenious men oblige them either to go on in the way of their fathers & not spend their time which would be devoted to the increase of their own fortunes in making improvements for an ungrateful public, or else to emigrate to some other Country that will afford to their inventions the protections they may merit?*

While written many decades after his initial work on the steam engine commenced, Watt hinted that without the patent systems, he would never have bothered: "Would to God the money and price of the time the engine has cost us were in our pockets again, and the devil might then have the draining of mines in place of me" (Smiles 1865, p. 296). The reality though, was that the patent system seems to have had no influence on the experiments that led to Watt's historic insight. His countless hours of spare time and devotion were at least originated and sustained through scientific curiosity. It was not until he conceived of the separate condenser and the fact that he required financing to carry out his vision, did likely begin thinking about a payoff. The irony that the separate condenser monopoly blocked the development of the next equally useful innovation, the compound engine, would have been lost on Watt. In an especially karmic ironic twist, Watt was himself prevented from implementing the use of a crank and flywheel, since James Pickard had already patented the method in 1780. Watt wasted precious time inventing a beautiful alternative, the sun and planet gear. However, it was not as efficient as the Pickard device, so in 1794, Boulton and Watt immediately adopted the economically and technically superior crank (Boldrin and Levine 2008, p. 2).

What occurred after the expiration of the Fire Engine Act of 1775 illustrates how patents actually encourage certain pricing arrangements over others. Frederic Scherer notes in the conclusion of his examination of the infamous patent: "Had there been no patent protection at all,… Boulton and Watt certainly would have been forced to follow a business policy quite different from that which they actually followed" (Scherer 1986, p. 11-12). They predominantly extracted licensing royalties, as they only managed the assembly of the engines by the purchasers, while independent contractors actually produced the parts. It was not until 1800 when Boulton and Watt actually started to manufacture their own engines. Without patent protection, they exploited their experience which gave them an advantage in quality, and thus allowed them to retain their high prices (Thompson, 1847, p. 110).

It is likely that Boulton and Watt broke even after just 8 years in business and were able to maintain first-mover market share for many decades (Boldrin and Levine 2008, p. 3). While the initial fourteen-year patent was likely instrumental in securing financing, the twenty-five year extension merely contributed to suppress innovation by his competitors. Indeed, reading about Watt from 1780 to 1800, one gets the picture that he spent more time in legal action to preserve his monopoly than he did to truly improve the engine. James Watt was arguably the first patent troll, getting other people to actually build the engine while he got rich collecting licensing fees. This is an economically rational behavior for the patent holders, but it comes at the expense of other technological improvements and economic progress.

Since ideas do not fall from the sky and Watt built upon other peoples' work, particularly Thomas Newcomen's, so do his steam engine ideas really belong to him? Ultimately, the question is whether the idea of the separate condenser was more like writing Hamlet, which would not exist without Shakespeare or more like Sherlock Holmes cracking a case? Was it a discovery of the "true" solution which always existed and would have eventually been discovered if Watt had not. The patent system, or the idea that one can own ideas, may have made Boulton and Watt rich, but also hampered the Industrial Revolution.

Patents Role in Innovation

North and Thomas (1973, p. 103-156) contend that France did not innovate new technologies as the State lacked "an efficient set of property rights". This interpretation has a number of weaknesses. We will never know the inventions lost to humanity as Watt[17] sunk his time and resources into merely protecting his patent. Indeed, prosecution of property rights violations in eighteenth century Britain, with no professional police force to rely on, were largely (over 80%) private affairs. While Britain's legal foundations for enforcement were present, the system lacked the administrative tools to carry out justice. Many inventors did not even bother to patent, as Christine MacLeod (1988) highlights in her chapter "Invention outside the patent system". Mokyr (1990) as well as MacLeod and Nuvolari (2006) call into question whether patents themselves were actually a benefit for inventors, concluding that they merely sparked a belief among inventors that a patent would guarantee riches.

The true lesson to be learned from the extreme litigation of steam engine patents in the late eighteenth century is that both Britain and France fostered an environment that recognized intellectual property rights. A number of authors have found that property rights were just as secure in all the leading European countries, regardless of the representative makeup of their governments (Allen 2009; Hoffman, Postel-Vinay and Rosenthal 2000; Pomeranz 2000). In fact, Rosenthal (1990) makes a good argument that property rights were actually too secure in France since profitable irrigation projects in Provence were halted due to property owners opposed to construction of canals or turnpikes across their land. Hoffman (1988) makes a similar case in the broader agricultural sector, as France allowed veto power where there were multiple owners of land, which often prevented better agricultural technologies. Despite the failures and deficiencies in the operation of the systems, both the governments of Britain and France clearly wanted to generate technological improvement and realized that requires promoting the creation of as many ideas as possible. France's explicit and sometimes inconsistent policy to encourage creativity and inventions did succeed in many cases. Even

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[17] A genius inventor not only for his separator steam engine condenser, but also copy machines for both paper documents as well as sculptures, which he inaugurated with the head of his old professor friend Adam Smith (Hills 2002, vol 3,pp 234–237).

though the development of the steam engine in the eighteenth century was dominated by the British, it was clearly not her patent system that favored Britain over France in its invention.

Attributing the British industrial revolution to the idiosyncrasies of its patent system (much inferior to the U.S. system) is a version of the fallacy that since Britain was first, their model must be the precise recipe of technological advancement. Joel Mokyr (2009, p. 52) reminds us that although Britain initiated "unprecedented growth, this took place *despite* rather than *because* of some of the institutional preconditions". Most of Western Europe was affected by Enlightenment ideas that stressed the importance of useful knowledge and that it could be fostered through unique national institutions. These countries would actively investigate their neighbors' systems to see what worked elsewhere, blending foreign and domestic ideas to create a complex and often backwards system to incentivize inventors using a mix of the market and experts. To plainly see how little Britain and France differed in the results of these efforts, one merely needs to look at the failure outside Western Europe to come up with anything remotely as successful in encouraging innovation. In other words, it was not the details of the patent systems that mattered; it was the fact that they existed, which suggests that the states realized the importance of protecting intellectual property rights in stimulating invention.

Industrial Espionage

Taking stock of movies and popular fiction illustrates how popular espionage is for modern audiences. Its combination of fear, ingenuity, deception, patriotism and danger translates perfectly to the screen or written word. While one would be tempted to choose James Bond over reading about industrial espionage in eighteenth century Western Europe, there are many bizarre and amusing aspects in the somewhat common practice. The first industrial spy was probably a French Jesuit who brought knowledge of porcelain making from China to France. The British ended up swiping those secrets from the French, which launched Britain's high-end porcelain industry.

Britain and France spent decades pilfering from one another. Even one of this story's heroes, Matthew Boulton managed to steal the French technique of gilding (ormolu) to make shiny brass and bronze buttons, buckles, and watch chains. Both Boulton and Watt were the target of a Russian attempt to seduce them to Catherine the Great (Musson and Robinson 1969, p. 224). Mokyr (1990, p. 107) remarked, "Britain had no monopoly on invention, but when it was behind, it shamelessly borrowed, imitated, and stole other nation's technological knowledge". However, it was the French who were the most frequent and blatant practitioners of industrial espionage on Britain in the eighteenth century (Harris 1998).

While France lost a number of great minds as religious or political exiles, they gained one ingenious British industrialist, John Holker, a disaffected Jacobite whose unsuccessful attempt at restoring the Catholic Stuart kingdom in Britain led him to serve the French crown in the manufacturing of textile machinery. In his position as France's Inspector General of Foreign Manufacturers, he recruited a number of British artisans to join him in his factory in Rouen and even convinced his son to bring him stolen blueprints (and possibly a disassembled version) of the "spinning jenny" in 1771, which vastly increased the production of French yarn (Harris 1992, p. 168). However, a mere stolen sketch or written account of a trade secret was not easily implemented abroad. As Holker wrote, "good information would make little impression on a workman, stubborn in his system and habits, it is by example that one may arrive at proving the true situation to him" (Vayssiere 1967, p. 284). Holker and other émigré managers found the best routes and methods to recruit and retain skilled English workers. They always had other English workers accompanying the new recruits to avoid them running away or being lured away to another firm. They often found Catholics or unmarried workers who might be enticed by a French dowry (Harris 1992, p. 168)

To stem the tide of industrial theft and brain drain, the British Parliament passed several measures aimed at stemming the flow of people and ideas. Just as the famous glassworkers of Murano would be sentenced to death for emigration, the British law forbid skilled workers from migrating to other countries. They would also punish recruiters with a fine of 500 pounds for every enticed worker. Lastly, they prohibited the export of most machinery (the steam engine was an exception). The constraints certainly delayed the diffusion of technology and knowledge, but thousands of English craftsmen exploited their unique skills to garner even higher wages abroad (Harris 1992, p. 166).

French espionage of British industry did not focus on steam engines until the late eighteenth century, when a number of attempts to penetrate Boulton's works were made. In 1777, a French foreign officer snuck into Boulton's own office, which had a sign above the door stating, "entry to these works forbidden to all persons whatsoever, because of the problems which have already arisen from it" (cited by Harris 1992, p. 169). The spy was caught shortly after making copies of drawings, but managed to flee back to France before his arrest. Another attempt was made by Government scientific advisers, Macquer and Berthollet, who optimistically wrote of "a means to upset and destroy (British industrial) superiority". They described Watt as possessing "the greatest genius for mechanics" and even quoted the King of England who "talked of him in the most honourable terms". They devised a pretext whereby Boulton and Watt would replace the water-powered water supply system of Versailles with their new steam engine, only to keep them in France with multiple steam powered business arrangements. The letter ends with an optimism that would not be justified until one hundred years later: "I dare to think we might soon be within measure of having nothing to fear from English industry" (cited by Harris 1992, p. 169). As intellectual property rights were not enforced across borders, the Savery/Newcomen or Watt patents would not prevent a copy being made in France, but the cost of coal prevented that opportunity to be exploited.

Paying close attention to the technologies which were successfully appropriated, those which failed in their replication attempts and the methods in which the knowledge was obtained, can provide tremendous insight into the French strategy and technical skills available. France tended towards espionage, while Sweden would offer to pay for trade secrets. Possibly as a response to the centuries of warfare between Britain and France, the French would commonly use terms like "national rivals" or "natural enemies" when making the case for obtain English processes (Harris 1992, p. 165). It is important to remember that this does not shed any light on French versus English morality, but Britain just had more to offer and the French had more to learn.

The French had a national security interest in the modern coke smelting and iron-working techniques practiced in Britain. The French were so desperate that they went as far as kidnapping Swedish ironworkers to help them establish an iron industry (Cipolla 1972, p. 50-51). In 1764, the French monarchy dispatched a young French engineer named Gabriel Jars, in order to learn the latest techniques in coal mining and how to use coke in iron production. John Holker organized the espionage mission and Jars was actually well received at British foundries and forges[18]. Upon his return, he proposed a government and private funded modern ironworks using coke blast furnaces (Clout 1977, p. 454). Le Creusot (not to be confused with the more modern and colorful French cookware manufacturer) was established in a prime location close to the coalmines of Burgundy with state-of-the-art equipment (Harris 1992, p. 170). The only thing it lacked was the technical expertise.

As promised, John “Iron Mad” Wilkinson makes another appearance, this time taking his cannon boring and coke smelting technology to France. Wilkinson would not participate in a joint venture with the French government, but did form a private arrangement with a fellow iron connoisseur, Marchant de la Houliere. They agreed that John’s younger brother William would make the move to France. Houliere foresaw cannon manufacturing in France with English expertise would not only build a better cannon at the same price as before, but also profit from exports. That dream was never realized and the endeavor ended in failure during the French Revolution, although William Wilkinson made a lot of money for his services (Weightman 2007, p. 27-32).

The failure of the French experiment at Le Creusot demonstrates that technologies will not be invented or adopted until they are profitable. The iron smelted at Le Creusot was excessively expensive, first as it takes time to adapt procedures to local materials, but also because the works never produced at capacity. Moreover, even with the close location to the coalmine, the Wilkinson coke furnaces were just barely cost-effective in England. In France, everything else would have to be perfect in order for the technology to be at least on par with the cost of charcoal furnaces (Allen 2009, p. 233). This is supported by the eventual installation of a charcoal blast furnace, bringing French techniques more in line with relative factor prices. Pressure to produce cost effective iron would lead the French back to charcoal, but that also meant that their adoption of coke-smelting would have to wait until the price of coal relative to charcoal made it worthwhile and/or the fuel use in coke furnaces dropped significantly. In fact, this is precisely what happened as the works at Le Creusot were taken up again in the 1830s. There is a happy ending to this story as the works eventually became “the greatest establishment in the French iron industry” after installing the latest fuel efficient blast furnaces (Henderson 1961, p. 100).

Given the intensity of efforts by the French to transfer British technology to her soil, often through espionage, it is telling that her labors bore only slow fruit. Even after they realized that you could not merely build a machine from a stolen blueprint, the new recruits of English craftsmen were unable to replicate the process that worked so well at home. First, there were the vastly different varieties of coal and other inputs to contend with. Also, they failed to recognize all the organic skills and equipment that were ancillary, yet essential, in getting a new technological process to work.

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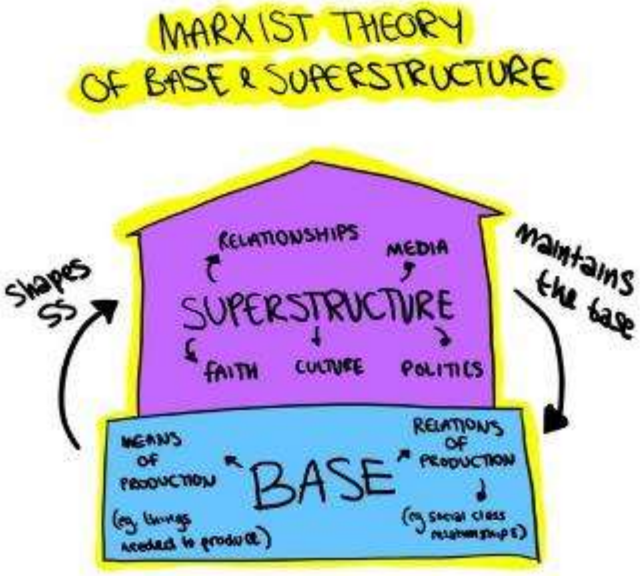
[18] I suspect that some British industrialists thought their technological lead was so great that it didn’t matter who saw their works. They probably also took national pride in the fact that the French wanted to learn from them.

Social Structure, Political Institutions and Religious Influence

Political scientists can easily accept that cultural beliefs and norms have inspired societal transformations, such as the American or the French Revolutions, but mainstream economics still questions ideology and culture's effect on economic outcomes. Karl Marx set the stage asserting that beliefs will adjust themselves to a society's economic system. The economic base is itself determined by more fundamental forces such as technology, geography and demography. In his study of the transition from feudalism to a capitalist mode of production, he posed a materialist way of understanding history, in which the material conditions of our existence (base) determines everything else in society (superstructure). While the thought would make some Chicago School economists cringe, the field of economics has largely inherited this Marxian belief, albeit without the revolutionary implications. The widely held belief among economists is that ideology is mostly endogenous to economics and certainly does not shape the economic environment.



On the other side of the spectrum are those daring economists who believe that culture and ideas are what really matter. They point to economic sea changes in history where even deeply seated vested interests have been overturned by revolutions in politics, culture or popular belief. As usual for theories of social sciences, the reality is somewhere in between, given the complex interactions that actually occur between the base and superstructure (or economics and wider culture).

Most comparative studies of the Industrial Revolution have focused on economic or political institutions, such as the power of the sovereign or property rights, which set the rules of the game (Acemoglu, Johnson and Robinson 2005, p. 453). However, more recently there is a realization that the ideas of potential innovators or entrepreneurs actually mattered more (McCloskey 2006). This is where an interaction becomes apparent, as ideas do not just fall from the sky. Rather, they occur within an environment where part of the population, which is usually urban, can take time to think and experiment rather than toiling in the fields.

Inventive Culture / Class

Imagine yourself as an artisan or farmer with an idea for a technological innovation in a pre-modern economy. However, having been taught a certain trade technique that has been refined for many generations, to question that wisdom would equal disrespecting ones' ancestors. Actual access to knowledge, whether technical or scientific, was practically non-existent. Even large-scale business owners did not understand the concept of systematic research and development (R&D). There was little motivation or support to take on a risk or to experiment, especially since technical success was usually incredibly small and one wrong move could spell financial ruin or starvation. It was within this environment that a small group of inspired and obsessive individuals began to take shape in Western Europe and was primarily concentrated in Britain.

It has been widely accepted that Britain possessed an unparalleled advantage in industrial innovation due to its relatively commercial and educated population. Mokyr (2009, p. 190) wrote the key to British technological success "was that its rich endowment of competent skilled artisans gave it a comparative advantage in the adoption of new techniques and their improvement through micro inventions". A more contemporary 1803 account by the French political economist, Jean-Baptiste Say, remarked that "the enormous wealth of Britain is less owing to her own advances in scientific acquirements, high as she ranks in that department, as to the wonderful practical skills of her adventurers in the useful application of knowledge and superiority of her workmen" (Say 1821, Vol. 1, pp. 32-33). These views emphasized the fact that inventors were not randomly found in any population, but rather were nurtured from a narrow social class with particular characteristics. An analysis of the creation of that class and its characteristics would allow a comparison between Britain and France and if it could have played a role in the invention of the steam engine.

Who were these Inventors?

A number of brilliant studies (Khan and Sokoloff 1993) (Crouzet 1985) have investigated in detail the characteristics of great or important inventors of the early Industrial Revolution in order to better understand and explore their connections with science and experimentation, as well as their social background. In addition to Thomas Newcomen and James Watt, many of these inventors, such as Abraham Darby and John Wilkinson have previously been noted in this study, given their influence on the development of steam engine technology. Robert Allen's (2009) database contains numerous insights into the social and occupational class these great inventors were born into. The following table combines the Allen database with the social index database of Lindert and Williamson (1982)[19] showing how many key inventors were born into certain occupational classes and their percentages, as well as a comparison with the percentage representing the English population as a whole.

Table 3 - Important Inventors: Father's Occupation:

	Number of Great Inventors	**Percentage of Inventors**	**Percentage overall England**
Aristocracy, gentry, clergy	8	11,9 %	3,5 %
Merchants, lawyers, capitalists	22	32,8 %	4,6 %
Manufacturers, artisans, shopkeepers	24	35,8 %	20,9 %
Mixed farming and craft	5	7,5 %	
Farmers, yeomen	6	9,0 %	18,0 %
Laborers, husbandmen	2	3,0 %	54,9 %
Total	**67**		

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[19] Which itself is based on, but drastically improved, the 1688 social tables of Gregory King.

The table illuminates how nonrandom the inventor population is by revealing that the probability of becoming an inventor increasing with the father's income and status (assuming that income rises the farther from farming and labor one gets). In fact, the majority (almost 70%) of the key inventors were born into a commercial class of merchants, artisans and manufacturers. It also illustrates how many more inventors come from these classes compared to their relative size in the English population. Mokyr (2009, p. 101) stresses the class dimension of the Industrial Enlightenment noting, "it was a minority affair confined to a fairly thin sliver of highly trained and literate men".

The reasoning from this table could follow that the larger the non-agricultural classes are represented in a population, the higher the likelihood of generating inventors. This is where the British example shines. The non-agricultural share of the population increased from 26 percent to 65 percent between 1500 and 1800 (Allen 2009, p. 260). France does not have reliable population numbers that can be compared, however in an estimate presented to the Assembly of Notables in 1787, its urban population was hardly two million while the total was twenty-three million, or less than 9 percent (Sée 1927/1968, p. 8). If the average propensity to invent is increased among an urban population, France was subject to a significant disadvantage. Although in absolute numbers, France was the largest country in Europe and almost three times the size of Britain, the apparent percentage difference is drastically diminished.

Human Capital by Apprenticeships

Another area where Britain showed its strength in cultivating an inventor class was its great endowment of human capital. Cressy (1980, pp. 118-74, 177) compiled data on the proportion of those who could sign their names for the various social strata in England in 1700. Again, superimposing this data onto Allen's great inventor database, we unsurprisingly find that the landed classes, such as rich merchants, lawyers and government officials were fully literate. Shopkeepers and manufacturers also showed impressive levels with a 60% literacy rate in rural areas and 90% in London. Small-scale farmers and laborers had between 15-20% literacy rate, which Reis (2005) points out was largely to read religious tracts or pulp fiction. Mitch (1993, p. 292) also iterates that the economic return of literacy and numeracy for merchants and inventors was much greater than for farmers, since correspondence and keeping records and accounts was critical in these fields. An illiterate inventor would be hard pressed to draw up contracts, engage apprentices and possibly apply for a patent. It is important to remember that barely half of Britain's population could sign their name at marriage (Mitch 1993, p. 267). David Mitch (1993, p. 303) has exhaustively examined the role of human capital in England's Industrial Revolution, only to find that "there is little evidence to suggest that education played a central role". This also indicates that the Industrial Enlightenment was not a working class mass-phenomenon, but rather isolated among Britain's few skilled innovators.

Humphries (2003) notes how elementary schooling in reading and writing followed by an apprenticeship became a common educational trajectory in seventeenth century Britain. The apprenticeship path was followed by many of the steam engine innovators. Thomas Newcomen was educated by a nonconformist scholar in Dartmouth and then apprenticed as an engineer. Steam technology in the nineteenth century was pioneered by Richard Trevithick, who was the son of a mine manager, who taught him the trade after attending the local school.

The hero of this story, James Watt, exemplified the eighteenth century Scottish enthusiasm for learning. Given the relative poverty in Scotland and the ample opportunities in Great Britain, the territories' most learned and ambitious would find employment in the south. While he was born into a very literate family (his grandfather was a teacher of math and navigation while his father was a shipbuilder and land surveyor), Watt actually had very little formal schooling. At the age of eighteen, Watt moved to London to apprentice as an instrument maker, but he did not qualify as he was too old. Watt was able to exchange one year of his labor for the opportunity to learn how to repair the era's most advanced technologies (Dickinson 1936, p. 15-22).

Britain's unintended focus on human capital was not only a fertile breeding ground for great inventors, but also for the innovators who would capitalize on eliminating the bugs and problems of an invention[20]. While Newcomen and Watt deserve to be among the ranks of great inventors for their revolutionary designs, but what really transformed the steam engine from a coal devouring inefficient pump for draining mines to a cost-effective machine that could power iron bellows, factory machines and even trains and ships, was the largely unacknowledged army of micro-inventors. These skilled engineers formed what Rosenberg (1976) called a "collective enterprise" as they experimented and tinkered with the machine to better adapt it to local conditions. Although the result was a revolutionary macro-invention, James Watt working on a model of a Newcomen machine is a perfect example of this kind of local learning. He would also visit the assembly sites to get a better idea of how the engines worked in practice and experiment with improvement ideas. Birmingham in the late eighteenth century would be reminiscent of Silicon Valley today, where entrepreneurs, venture capitalists, inventors and engineers cluster together to capitalize on smooth information networks and local synergies (Aoki 1999).

What lead Britain to its superior level and diffusion of mechanical skills?

Britain's crafts guilds were considerably weaker than their counterparts on the Continent in the eighteenth century. This allowed resourceful craftsmen the freedom to learn and exercise the skills most beneficial to them. The ambitious were able to use the market to exploit new ideas, whereas guilds elsewhere would typically encumber new entries by regulating training and procedures. However, contrary to the common wisdom of Adam Smith, recent studies have found that the more powerful craft guilds in France did not necessarily have a negative impact on innovation (Epstein and Prak 2010, p. 2-3).

David Landes (1969, p. 61-63) makes a compelling argument that British advances in clock and watch manufacturing, skills that were easily transferred to textile machinery and wheelworks, first provided them with an advanced understanding of how to replace men with machines using more inanimate power. Even in the early eighteenth century, Newcomen and his assistant were "at a loss about pumps, but being near Birmingham and having the assistance of so many ingenious and admirable workmen, they soon came to methods of making the pump-valves, clacks, and buckets" (Desaguliers 1744, p. 533). By James Watt's time, Boulton's workshop in Soho was home to countless highly skilled craftsmen who came from various apprenticeships. Watt noted that many had originally been trained as "millwrights, architects

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[20] This also applied to foreign inventions too, as in the case of the De Girard wet-spinning process of flax and Jacquard's loom.

and surveyors" who easily transferred their practical skills and dexterity to a new in-demand occupation (cited by Jones 2008, p. 126-127).

England's early reliance on coal also stimulated its relatively large innovative class of mechanics and engineers. The first Savery and Newcomen steam engines familiarized mine owners and engineers with technological change and the advantages of observation and experimentation in cutting costs. Harris (1976, p. 168) also emphasized that England pursued a lone path in developing coal and other related industries, which required practical skill honed from "learning by doing" in the absence of a scientific understanding. Britain's abundant supply of skilled artisan mechanics relative to France made it much easier for her engineers to realize their inventions. Without these anonymous, yet indispensable workers, Britain would not have become the workshop of the world.

Technological Experimentation: John Smeaton

As noted previously, the scientific method revolutionized the form of science throughout Western Europe, but it was predominately in England where it was applied to technology. While this was not a new effort and certainly not isolated to Britain, it was the British who excelled at it in far greater numbers. One particular figure symbolized this spirit, although he never made a spectacular breakthrough that would warrant an entry in a school history book. John Smeaton is characterized by Joel Mokyr (2009, p. 98) as the very personification of the Industrial Enlightenment, not only for his contributions to steam engines, but also water mills, bridge construction, harbor engineering and lighthouses. Rosen (2010, p. 152) called Smeaton "the most brilliant engineer of his era – a bit like being the most talented painter in sixteenth-century Florence".

He did not start out on the path to engineering greatness, but rather was to follow in his father's footsteps as an attorney. In an era where one did not easily change careers, his family's secure middle class background allowed him to drop his studies and move back home to work as a mechanic (every parent's dream). He set up shop in London a few years later. Far from a working class mechanic, his talents were quickly recognized and he became a fellow of the Royal Society. In 1756, he both invented a cement that would set even when submerged in water while rebuilding a lighthouse *and* published an awarding winning paper entitled *An Experimental Enquiry Concerning the Natural Powers of Water and Wind to Turn Mills*. The study documented the various efficiencies of different types of waterwheels, advancing the millennia old-field light-years ahead with merely seven years' worth of research (Smeaton 1760). Prior mathematicians, including French scientist Antoine Parent, attempted to compare the benefits of the "undershot" wheel versus the "overshot", where water falls into buckets from the top. Smeaton realized that

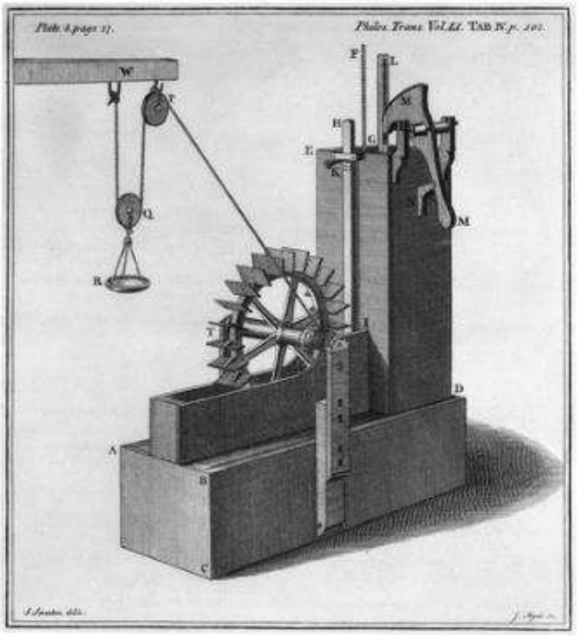

Figure 13 - Smeaton's model waterwheel

experimental comparison was the only way to really solve the mystery. After constructing a twenty-inch water wheel, he promptly got to work on the century's most meticulous experiment, which tested varying components one at a time while holding others constant (Farey 1827, p. 168)[21]. The results disproved Parent's scientific conclusion, causing Smeaton to lose faith (partly justified) in the scientists of his day. He also gifted Britain, where 70% of power was generated by waterwheels, with the breast wheel, which was two times more efficient than the undershot (Reynolds 1983, p. 280-282)

This methodology of approaching a problem by systematically varying parameters through experimentation in order to improve a mechanism was unheard of at the time. Concurrently with Watt, he worked on improving the efficiency of the Newcomen engine. Using experimental engines and careful observation and measurement, he developed the ideal specifications that had 25% greater efficiency than all others before Watt's separate condenser (Skempton 1981, p. 121). As a "thank-you" for his contributions, Boulton & Watt actually offered him the royalties on one of their installed engines (Rosen 2010, p. 155). In environments where the science behind the natural process is poorly understood, systematic trial and error seems to be the only way forward. James Watt wrote of the need to experiment commenting, "when one thing does not do, let us try another" (cited by Jones 2008, p. 172). While Smeaton's list of inventions is short, he became a hero in England for demonstrating a process to experimentally test the stream of inventions that were becoming increasingly available.

Allocation of Engineers

Smeaton was concerned that French engineers had superior schooling in mathematics, while British engineering education was "left to chance". Engineering was not an intellectual activity affected by the Scientific Revolution. Nonetheless, Smeaton trained engineers in his approach of careful investigation, measurement and testing. Perhaps in response the French domination of the field at that time (both Smeaton and Watt had to study French engineering books, since there were so few in English), he started a "Society of Civil Engineers", whose members referred to themselves as "Smeatonians" and eventually changed their name to the Smeatonian Society. Their motto, pulled from the Bible, advised engineers to work "all things in measure, number and weight" (Pacey 1992, p. 180).

Smeaton coined the term "civil engineer", which basically meant engineering that was not military. This was another profound difference between Britain and France, where engineers were predominantly employed by the military or government. The term "engineer" in France implied military man, while their British counterparts mainly worked in the private sector designing more efficient mills, lighthouses, steam engines and mining techniques (Mokyr 2009, p. 188). France did have superior schools setup for the purpose of supplying the crown with the best engineers, such as the École du Genie Militaire and the École des Mines (Ziegler 1997, p.28). This rationale continued through the Napoleonic era where the government preserved a monopoly on higher education which was geared to serving the interests of the State. This focus on building a reservoir of highly trained public services entailed the suppression of organizations which would be best suited in training the industrial arts. Charles Kindleberger (1964, p. 3-40) in writing about technical education and the French

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[21] Much like the modern economics tradition of Ceteris Paribus.

entrepreneur, notes that graduates of the grandes écoles in France focused their technical training on the glory of science, which would create products inelastic to price sensitivities, rather than those catered to the mass market.

Technological flows

The flow of technology and the associated skilled labor can provide indications to which country or region possessed a stronger inventive culture. It is also insightful to analyze the origins and transfers of the types of inventions, especially using the macro versus micro distinction. In the early stages of the Industrial Revolution, Britain was generally a net importer of macro inventions, especially in glass, paper and high-end textile industries (Mokyr 1990, p. 254). However, it was her mass of skilled technicians that improved, refined and made those inventions economical through countless micro inventions. A Swiss textile printer named Jean Ryhiner perfectly encapsulated this phenomenon writing in 1766 (cited by Wadsworth and Mann 1931, p. 413):

> *Everyone knows this nation (Britain) whose industry and stubborn patience in overcoming every kind of obstacle are beyond all imagination. They cannot boast of many inventions, but only of having perfected the inventions of others, whence comes the proverb that for a thing to be perfect it must be invented in France and worked out in England.*

The French state sought to repatriate technology with its origins on the continent, but vastly improved by Britain both through industrial espionage, but also the multitudes of British skilled emigres who tried to implement the same superior industrial processes they mastered in their homeland. France quickly found that the tacit skills of adapting and tweaking inventions would prove quite difficult to transfer from one country to another. In this respect, there is a clear first mover advantage since France was required to compress its "apprenticeship" into a much shorter period than the British originally used. Jean-Antoine Chaptal, the French industrialist noted that his country could not even compete with Britain after importing the same machine used in Britain. He noted the lack of detailed knowledge, experience and dexterity caused French prices to be twice those of British (Chaptal 1819/1993, Vol. 2, p. 430-431). This lack of technological know-how also explains why British industrial espionage was far more successful than French attempts, as the British tradesmen were better able to combine their skill with an "almost artistic judgement" (Harris 1992, p. 28).

It was not always a one-way transfer of technology, as Harris (1992) examined the interesting case of plate glass, where the British sought to acquire the French casting technique, while the French tried to imitate British coal furnace practices. Britain also imported foreign inventors and engineers, but the nature of their migration was quite different from the pull factors found among the British technicians who were lured by even higher wages for their skills on the continent. The revolutions in Europe provided a strong push factor for many innovators, many of whose inventions received a warmer welcome. The Swiss Aime Argand struggled with selling his revolutionary oil lamp in Paris, but later partnered with Matthew Boulton and received technical and legal advice (how to fight patent infringement) from James Watt in England (Wolfe 1999, p. 54).

Marc Brunel and the inventors network

The most famous British import from France was the Brunel family, who escaped France in 1793 as the revolution was taking a violent turn. The royalist-leaning patriarch Marc Isambard Brunel was enthusiastically welcomed to the newly formed republic the United States of America, where with a flash of insight, he devised an automated production of pulley blocks, which would improve the efficiency of the shipbuilding process tenfold. In 1799, he arrived London where he married his English girlfriend, who had barely escaped France herself a few years prior. In England, Brunel promptly met Henry Maudslay, the grandfather of the machine tool industry who, at the young age of eighteen, built the world's best lock (at least for 47 years) using special tools and machines. The lock was famously displayed in another brilliant English inventor, Joseph Bramah's shop, with an offer of 200 guineas to anyone who could pick it. Brunel struck a deal with Maudslay to construct the cold iron machines for £12,000, which would be more than $1 million in current dollars (Cooper 1984, p. 183). The factory has been called "the first instance of the use of machine tools for mass production" (Gilbert 1965, p. 1). It used Boulton & Watt engines to power the saws, despite the Royal Navy's panic that the newfangled contraptions would "set fire to the dockyards" (Cooper 1984, p. 184).

This genius trio is highlighted here, not only for their fascinating histories, but also to emphasize the complex synthesis of inputs and skills required for an invention to become successful. Even if the Reign of Terror had not attempted to take the lives of Brunel and his girlfriend, his invention would have definitely failed in France where machinists lacked the precision that Maudslay had mastered down to thousands of an inch (Rosen 2010, p. 236). It was not necessarily the skill of French machinists that is to blame, but rather the skills and development of her struggling iron industry, which by the late eighteenth century, was readily available in high quality in England. A nation's superior artisans alone could not engineer or design invention, just as inventors would fail to actually build their contraptions without expert mechanics. While the exceptionally skilled artisan Thomas Newcomen miraculously got the steam engine to work, it took the better-trained minds of Smeaton and Watt to drastically improve the technology from a powerful water pump to the nineteenth century's dominant power source. It was Britain that possessed the perfect "combination of useful knowledge generated by scientists, engineers, and inventors with the existing supply of skilled craftsmen and an institutional environment that produced the correct incentives for entrepreneurs (Mokyr 2009, p. 196).

One last factoid taken from the biography *The Greater Genius* (Bagust 2005, p. 57) about Brunel the elder challenges the popular belief in Britain's laissez-faire government. Despite being paid more than £17,000 by the Navy and possessing numerous patents, including the poorly timed machine which mass-produced thousands of military boots just before Waterloo in 1815, he was incarcerated (together with his wife) as a debtor in 1821. To stop the attempts of Alexander I to recruit Brunel, the British government actually paid his £5,000 debt on the condition that he would not work for the Russian Tsar. This type of government intervention was typical for France, but the British government was desperate for Brunel's experience in order to build the Thames Tunnel, which was completed in 1842 with the valuable assistance of his son. Had this story continued into the nineteenth century, Brunel's even more famous son, Isambard Kingdom[22], would have played a prominent role for his numerous achievements in engineering and steam-powered transportation.

The rise of Britain sows the seeds of her downfall

Robert Allen (2009, p. 148) noted the irony that as Britain improved her technologies through countless micro-inventions and improvements, she destroyed her competitive advantage over rival nations. Once the steam engine and coke smelting technologies became sufficiently efficient in their uses of inputs (coal, ore, capital), the French rapidly shifted to mineral fuels adopting the most modern and advanced technologies. By that point, Britain had lost the advantage since technologies no longer favored her factor endowments (high wages and low of cost of coal). Her engineers actually invented an “appropriate technology” for France. Crafts and Thomas (1986, p. 643) concisely articulate this paradox:

> *The source of Britain’s industrial leadership in the nineteenth century was a favourable endowment of natural resources, combined with a stock of labour sufficient to exploit these advantages; Britain’s handicap in the later part of the century was a scarcity of the human capital which was an essential input to the technologically progressive product-cycle industries that dominated the Second Industrial Revolution.*

Indeed, British education was at its best outside its schools where it nurtured technical, applied and pragmatic knowledge in producing things cheap and durable. This system clearly benefited Britain during the First Industrial Revolution, where technological advances were not dependent on understanding scientific principles, but rather intuition and persistent experimentation. As the nature of technological advancement changed in the latter half of the nineteenth century, the innovative class schooled on the job as apprentices quickly turned into an obstacle, as new technology creation began to require mastery of formal sciences.

Political

Britain’s Glorious Revolution and the Industrial Revolution

Many economists who naturally see incentives as the driving force of innovation, point to Britain’s unique political landscape as the causal factor in developing markets and her economic success during the first stage of the Industrial Revolution. This view was eloquently exemplified by the Nobel prize winning economic historian Douglass North and his political science partner Barry Weingast in their article titled “Constitutions and Commitment: The Evolution of Institutions Governing Public Choice in Seventeenth-Century England” (North and Weingast 1989). They cite the Glorious Revolution of 1688-9 as the breakthrough when Parliament obtained more power than the King, which created secure property rights. It is unclear however, whether this political transition took 80 years to germinate or there was no causal link with inventive activity. The latter seems more probable since the Dutch Republic had established strong property rights even earlier, but channeled its focus on international trade rather than invention. Also, Gregory Clark (1996) makes a compelling argument that property rights were just as secure in Britain prior to 1688. However, the argument that the

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[22] Voted second in a 2002 BBC poll of the one hundred greatest Britons, just behind Winston Churchill, but ahead of Shakespeare, Darwin and Newton ("Churchill Voted Greatest Briton" 2002).

Glorious Revolution sparked the Industrial Revolution deserves examination, but into the mechanisms of causation, namely low taxes and patents.

The view that Britain owed its initial technological success to her low taxes and government debts is shared especially among economic liberals, such as the Cato Institute and their loyal contributor, the great economic historian Deirdre (Donald) McCloskey (Floud and McCloskey 1981). They[23] contrast Britain with France's Ancien Regime assuming it must have imposed a far greater burden on its citizens. The reality in 1788 was that Britain's tax rate was almost double that of France: 12.4% of GNP versus 6.8%. Furthermore, Britain's national debt was three times greater than the Ancien Regime. France did suffer from shaky finances in the eighteenth century, but it was the inability to collect sufficient taxes that actually served to constrain its spending. The annual debt service ratio between the two countries was quite comparable, with 39% in France and a slightly higher 48% in Britain (all figures from Weir 1989, p. 98).

The British state eventually did gain a tremendous advantage over the French with its extensive access to credit at relatively lower rates of interest. This has led many economic historians to assume that this was due to France's failure to adopt British-style institutions (Velde and Weir 1992). However, while it is clear that the French monarchy was forced to borrow at significantly higher interest rates than the British government, it is less obvious that institutional reform in France would have improved its credibility as a borrower.

David Stasavage's (2003) landmark study *Public Debt and the Birth of the Democratic State: France and Great Britain, 1688-1789* surprisingly demonstrated that constitutional checks and balances are "neither a necessary nor sufficient condition" for improving the credibility of credit worthiness. This is supported by the fact that Britain still experienced interest rate volatility following the Glorious Revolution and at times borrowed at rates just as high as the French monarchy in the early eighteenth century (Stasavage 2003, p. 95). For France, the evidence is a bit more speculative, but Stasavage (2003, p. 23-24) finds that its defaults would have occurred even if their national representative institution, the Estates General, was reconvened following the death of Louis XIV in 1715. This is also the case for the French Constituent Assembly in 1789.

Despite their differing political institutions, both governments established national banks and other bureaucratic institutions to ease access to credit. France in the latter half of the eighteenth century quickly developed decent private financial markets, despite the monarchy's lack of credibility (Hoffman, Postel-Vinay and Rosenthal 2000). History and the data does not support the simple explanations that Britain's political institutions following the Declaration of Rights of 1689 directly led to innovative activity among Britain's artisan and merchant classes, despite it imposing severe restrictions on the Crown's arbitrary rule. In fact, these discrepancies should lead to inquiries into why Britain's economy soared during the eighteenth century, despite its high tax burden.

The final mechanism of political institutions leading to invention is the creation and enforcement of intellectual property rights (North and Thomas 1973). This paper has previously noted the limitations and weaknesses of the English patent system, which is

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[23] See also Schultz and Weingast (1996)

displayed numerous times in the history of the steam engine. It has also highlighted how France was able to spur invention by a set of alternative incentives.

French Dirgisme

The French experience with mercantilism is often contrasted with the Anglo-Saxon market approach as support for Britain's economic success during the Industrial Revolution. Numerous revisionist historians, such as Keyder and O'Brien (1978) and Roehl (1976), have underscored how successful the French regime was in constructing their desired national economy. This is a troubling fact given the tremendous evidence against state-driven industrial policy, but that should not be grounds to dismiss France's partial success in the eighteenth century. Keyder and O'Brien (1978, dust-jacket) argue "that there were two paths of economic growth to the 20th century and (are) provocatively inclined to see a more humane and no less efficient transition to industrial society in the path chosen by France".

Keyder (1985, p. 308) later points out that "the continuity of the importance of the state is what sets France apart". Colbert and the Crown established, regulated and protected countless industries, such as the wool factories of Van Robais and Gobelin, where government officials carefully regulated the quality of production. While this level of minute detail must have entailed an extreme burden for the French bureaucracy, state involvement in Britain was not uncommon, especially through taxation policy to fund the "Second Hundred Years War" (O'Brien 1988, p. 1-32). It is easy to use notions from modern economic theory to assume that France was held back due to its state dirigisme while England facilitated the "superior performance of free industry" (Landes 1969, p. 174). However, the Industrial Revolution that occurred in nineteenth century France was actually successful due to government efforts to guide, protect and support her industry.

A few examples highlighting the success of France's dirigisme were listed by Henri Sée in his 1927 study of the *Economic and Social Conditions in France during the Eighteenth Century*. One case worth highlighting is the state enterprise in coalmines. The capital outlays proved to be too steep for French mine owners until a 1744 decree that regulated mines so they could only be exploited by royal concession. The state recognized the strategic importance of coal mining, but private entrepreneurships failed to develop the industry. Only the monarchy was willing to spend millions on the necessary mining and steam technology required for ventilation and drainage. This does not mean that only government bureaucrats were in charge, but rather energetic and business-savvy managers led these "great capitalistic enterprises" as private stock companies (Geiger 1976, p. 17-22). The Compagnie des Mines d'Anzin for example had 600 horses and 4,000 workers, using 12 steam engines to mine almost four million hundred weights of coal bringing in tremendous profits (Sée 1927/1968, p. 172).

While Anzin became France's largest and most prosperous coal mining company prior to the Revolution, it can be seen as a testament to both the achievement and failure of France's interlocked world of finance, business and government. The state can provide critical direction and support of certain industries, but it is impossible to take all factors of economic ecosystem into account. For example, while the coalmine at Anzin was successful, transportation costs inhibited the industry from growing much larger than the single state-sponsored company. In other words, the French example shows that the State can play a powerful role in fostering industry, but not in creating an industry, especially when it runs against its own factor endowment bias.

France's state-sponsored Scientists and Inventors

Antoine Lavoisier

Figure 14 - Portrait of Antoine-Laurent Lavoisier and His Wife (David)

One last aspect in the differences in political institutions was the success of the French monarchy in developing scientists and inventors as extensions of the state. Fitting the rightful stereotype of the gentleman scientist, Antoine Lavoisier became commonly considered the father of modern chemistry for his role in transforming the science from a qualitative to a quantitative field. However, it was his involvement with the state that grants him a part in this paper. Lavoisier earned the hatred of the French peasantry for his role in the *Ferme générale*. In 1769, he purchased a share in the King's highly unpopular tax farm, which was basically an outsourced tax collecting company that incentivized its owners with hefty bonus fees. These proceeds largely funded Lavoisier's scientific studies, but the marvelous efforts of his wife also provided significant support. At the time of her marriage at the young age of 13 years, her father was a senior official in the *Ferme générale*. She would grow up to assist him in the laboratory, draw scientific sketches, translate English scientific documents for him as well as host parties where eminent scientists could network (Eagle 1998, p. 5).

Lavoisier performed numerous scientific studies for the French crown through the *Académie des Sciences*, including his guiding role in devising the metric system. He also served his country as head of the Gunpowder Commission, which proved to be a successful inquiry into how to improve the private munitions industry in both quantity and quality (Poirier and Balinski 1996, p. 118). In the wake of the Terror of the French Revolution, Lavoisier contributed his final act of service to the scientific community. While under arrest for his role as a former tax collector, he defended a number of foreign scientists living in France so that they would maintain their possessions and freedoms. The French sounding Joseph-Louis Lagrange, actually an Italian mathematician, who has been the bane of many economics students, was one of those saved by Lavoisier. He remarked on Lavoisier's death by guillotine "it took them only an instant to cut off that head, but France may not produce another like it in a century" (cited in Gould 1991, p. 355).

Nicolas Cugnot

The French government not only recruited its scientists to work in its service, but also aspiring inventors, including the genius Nicolas-Joseph Cugnot. He has been lauded as the inventor of the first automobile, or at least the first self-propelled mechanical vehicle, likely inspired by Papin's steam-powered boat. Trained as a military engineer, he started working with models of steam-engine-powered vehicles to solve the army's problems of transporting their cannons given the inefficiencies of horse drawn wagons. Twenty years prior to Boulton and Watt's rotary motion machines, he built one using a ratchet arrangement described in his book Éléments de l'art militaire ancien et modern (Cugnot 1766). In 1769, he was commissioned to build a three-wheel *fardier a vapeur* to replace the inefficient horse-drawn fardier, which was a huge two-wheeled cart used to transport guns and cannons. Alain Cerf (2009) wrote the authoritative book on the Chariot of Fire, providing the following facts about Cugnot's brilliant invention. After a number of iterations, Cugnot built a vehicle that itself weighed 2.5 tons, but was able to carry about four tons and travelled about 8 kilometers per hour. The front wheel supported the steam boiler and driver mechanism.

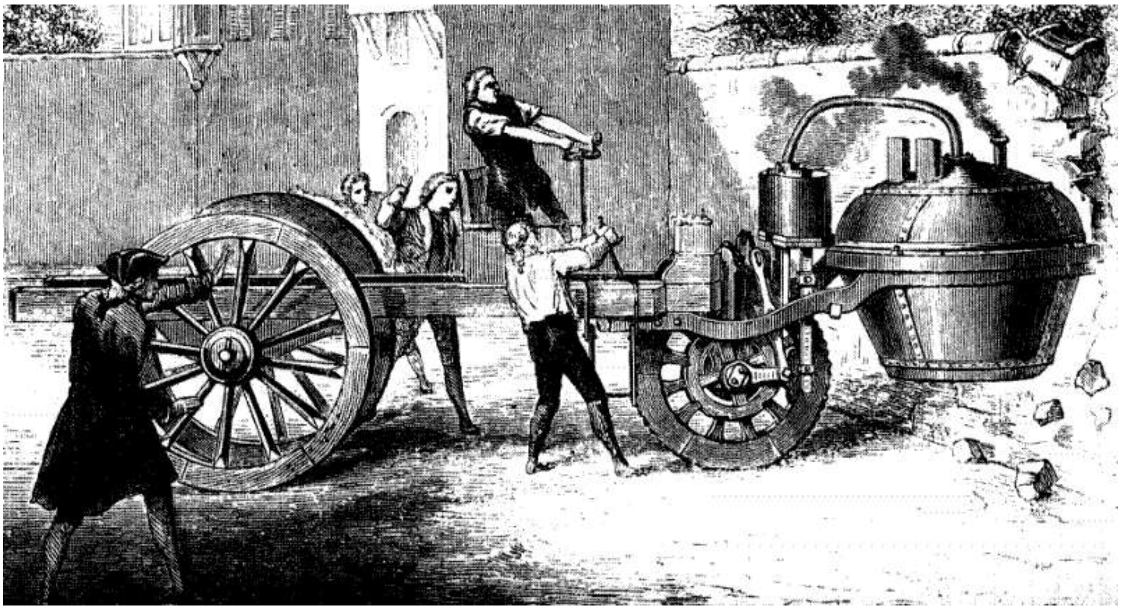

Figure 15 – Cugnot's Fardier (Woods 2012)

There is debate whether Cugnot also invented the first automobile accident, as an account from his 1804 obituary notes that his vehicle went out of control crashing into the Arsenal wall[24]. While Cugnot ironed out most of the kinks involved with the world's first automobile, his focus was on its mechanics and not that of the steam engine. This meant that the fire for the boiler needed to be relit every fifteen minutes and its poor design inherited much of the inefficiencies of a Newcomen machine. The project was eventually abandoned as Cugnot's military backers had moved on to other positions, but his work innovative enough to be awarded a pension of 600 livres per year from King Louis XV. Tragically, his pension was revoked during the French Revolution and he lived in exile for a number of years until Napoleon himself invited him to return to France, just before he died in poverty.

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[24] This study was largely inspired by viewing the actual vehicle during a visit to the Conservatoire National des Arts et Métiers in Paris.

The Pyroscaphe – the first steamboat

While the French lagged behind the British in perfecting the steam engine, they showed a unique vision and determination in applying it to transportation. Cugnot's work on a land vehicle as well as other French efforts in steam boating during the eighteenth century unfortunately failed, largely due to random events of human nature. Denis Papin's steamboat was successfully drove oars, but lacked a working steam engine. He planned to install an engine and present the vessel to the Royal Society in England (Ballot 1978, p.390). However, his dream was crushed as the boat was destroyed by boatmen in Germany who protested that they had monopolistic rights on the Weser River. It is likely that the true reason for destroying the boat was that they feared the automated mechanism for powering the oars, in true Luddite fashion (McCloy 1952, p. 30).

The *Académie des Sciences* offered numerous incentives, including cash prizes, to advance transportation technology. Many of these remarkable proposals realized the power of steam in powering boat by mechanical means, as documented in Gallon's (1735) seven volume set *Machines et inventions approuvées par L'Académie royale des sciences*. The interest in steam powered boating took off in the 1770s, first with a former military officer Chevalier Joseph d'Auxiron who had the brilliant idea of operating steamboats on major rivers in France (Seine, Loire, Garonne and Rhone). He recruited his lifelong friend and fellow army officer, Chevalier de Follenay. The company was given conditional monopolistic rights for fifteen years, if the *Académie des Sciences* deemed the invention seaworthy. Similar to Papin, the boat generated fierce hostility from boatmen and the boat was inexplicably sunk in the middle of the night (Ballot 1978, p. 390-392).

Another former army officer now makes an appearance, but first from his prison cell on an island near Cannes, where he was sentenced for fighting a duel with a superior officer. The Marquis de Jouffroy d'Abbans is reported to have dreamed of ways to automate the movement of ships as he viewed galleys sailing the sea from his window. Upon his release, Jouffroy and crowds of tourists visited the Périer brothers' Watt steam engine installed at Chaillot, near Paris, to supply the city with water. This gave him the great idea of propelling a boat using a Watt steam engine. He joined forces with a new company formed by D'Auxiron and Follenay, together with two other movers and shakers, Ducrest who maintained numerous connections including royalty, as well as one of the Périer brothers. A simple disagreement between Périer and Joffroy over the boat's construction proved fatefully ominous. Joffroy left the company and was surely satisfied to later learn that Périer's boat did not work (Figuier 1860, p. 162).

Joffroy worked on a few iterations of steamboats on the Saone at Lyons and in 1783 navigated the first steamboat, the Pyroscaphe, to the Isle Barbe on the river, before thousands of cheering spectators. Joffroy was given the same condition as the first steamboat company in order to receive monopoly privileges, however, the *Académie des Sciences* required the disregarded the demonstration at Lyons and required him to take "a boat up the Seine the distance of several leagues, proven or certified in such a manner as to leave no doubt on the value of your procedures" (Ballot 1978, p. 394-395). Jouffroy despaired over the great expense this would require and was never able to secure enough funding to transport the boat nor the steam engine to Paris. Périer, a brilliant mechanic and steam engine enthusiast, likely abused his membership in the *Académie des Sciences* in a jealous retribution that imposed impossible demands and denied all requests for financial aid[25] (McCloy 1952, p. 25). Like so many genius inventors of the time, Jouffroy would die penniless and forgotten, due to a small twist of fate that robbed France of the glory and profits of a revolutionary invention.

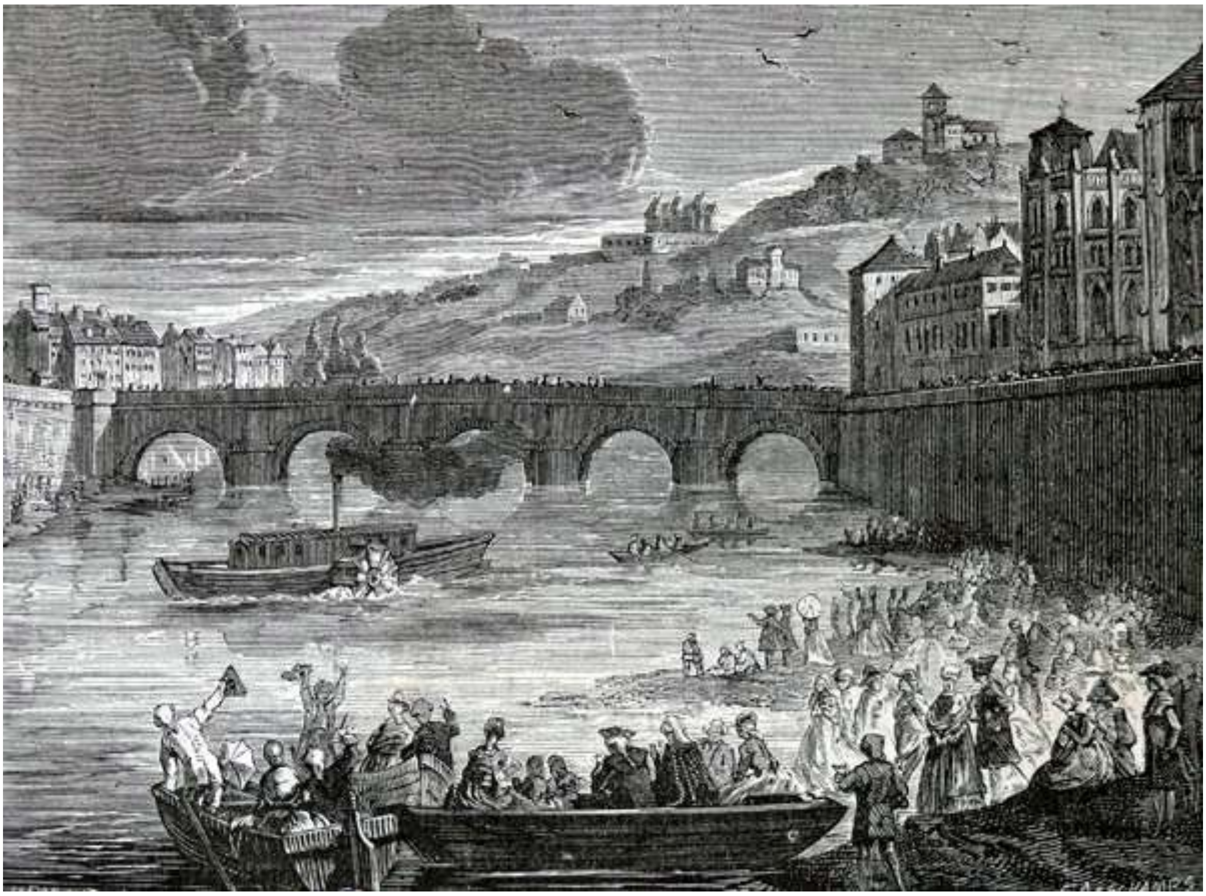

Figure 16 - Expérience du marquis de Jouffroy faite sur la Saône à Lyon, le 15 juillet 1783 (Figuier 1860, fig 86)

Religion

Attitudes towards Science

A recent controversy has erupted over whether religion stifles innovation, igniting the age-old debate over "religion's often tense relationship with science, free thought and disruptively novel ideas". A study published by the National Bureau of Economic Research titled "Forbidden Fruits: The Political Economy of Science, Religion, and Growth" found "a significant and robust negative relationship between religiosity and patents per capita" (Benabou, Ticchi and Vindigni 2015, p. 346). The paper emphasizes the various models of religion, such as the Western European model, which allows relatively free scientific inquiry or a theocratic[26] model where political leaders allied with their religion stifle scientific discoveries.

This distinction in helpful is examining the role religion could have had on potential inventors in Britain and France. Before the Scientific Revolution, knowledge in both countries were tied

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[25] There are a few examples where the *Académie des Sciences* allowed for local demonstrations or provided financial support to promising inventions (Figuier 1860, p. 168).

[26] I would argue that any rigid ideology can impede science, such as Soviet attempts to repress «bourgeois» scientific knowledge.

to an ancient heritage infused with “magical” traditions. As the great Enlightenment thinker John Locke once suggested, men (and societies) learned by progressing through experience from ignorance to knowledge. The Scientific Method slowly began to dismantle mystical beliefs as knowledge claims were validated by experimentation. In a world where nothing seemed certain any more, essential concepts, such as quantification, the difference between correlation and causation, and ceteris paribus brought the beginning of new scientific, moral and political certainties. Respected economic historians, such as Jacob and Stewart (2004) and Allen (2009, p. 268) treat the Scientific Revolution and Enlightenment as a pan-European affair, yet the Anglican and Catholic churches stamped a unique character on their adherents. Religious authorities in both countries reinforced the separation of Newtonian and experimental science in Britain from the Cartesian science of France.

As noted in the section discussing the science of steam, Aristotelian ideas impeded understanding of the vacuum and thus the invention of the steam engine. It could be argued that England was the farthest removed from the old clergy of the Roman Catholic Church following the Reformation under King Henry VIII. That movement, which created a unified church where clergy were dominated by the king, who led the church in working towards the national interests. Free thought was also aided in Britain after Parliament forbid the Anglican Church from censoring secular intellectual affairs in 1641. In addition, the immense political and religious struggles in Britain did not lead to a single state church that would impose a rigid orthodoxy. Voltaire depicted England’s religious toleration as a nation of many faiths, but only one sauce. He added, “if there were only one religion in England, there would be danger of despotism, if there were only two they would cut each other’s throats; but there are thirty, and they live in peace.” (Porter 2001, p. 64-65). To promote harmony among the different faiths of the kingdom, the Anglican Church eventually adopted the Baconian program of empiricism and experimental methodology as a direct opposition to the Catholic view (Jacob 1997, p. 27, 29, 54). It used the Newtonian clockwork universe as a model of godly wisdom and harmony, where all planets are subject to simple natural laws. The unique character that the Enlightenment took in religiously liberal England allowed the pursuit of one’s self interests. Roy Porter (2000, p. 99) cogently remarked that the English Enlightenment took place *within* rather than *against* Protestantism.

While papal authority in France was much weaker than in Southern Europe, the French Catholics were more antagonistic against Protestant ideas, culminating in the 1685 revocation of the Edict of Nantes, which previously granted religious freedom to the country’s Huguenots. Whether the French suffered a significant economic loss due to the expulsion has been hotly contested. The definitive study[27] provided by Warren Scoville (1960) titled *The Persecution of Huguenots and French Economic Development, 1680-1720* found that of the two million French Protestants, only 200,000 (only one percent of the total population) left the country and the rest merely “converted” to Catholicism. Scoville’s systematic investigation of the persecution on each sector in the French economy either found no effect or a very limited negative impact. However, this paper has already highlighted the loss of Papin and speculates whether a more tolerant environment could have fostered the completion of a commercially viable steam engine in France.

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[27] Almost 500 pages on such a narrow topic!

Figure 17 - The Academy and Its Protectors (Le Clerk 1671)

Rather than completely repress scientific thought like the Catholic Church in Spain and Italy, France took a slow road in accepting the ideas of the Scientific Revolution. Rene Descartes, France's greatest scientific and philosopher mind was a devout Catholic, yet found that the more tolerant and free-thinking Netherlands was a more hospitable atmosphere. France eventually embraced Cartesian science and became the home of some very important scientific contributions. French Catholics used Cartesian logic to reconcile the new mechanical science with the church, even as they maintained a belief that God could miraculously intervene in the universe. In testing hypotheses and discovering knowledge, logic was a substitute to experimentation, which was considered too unpredictable.

Just as in England, the State had amassed more power than the Church. Attempts by the French monarchy to compete with the British economy allowed a much more practical view of science. Colbert was instrumental in this regard and played a decisive role in the creation of the *Académie des Sciences*. Although, in contrast with Britain, where scientific writings were written for a widespread audience, France's scientific community catered more to the intelligentsia (Gillespie 2004).

Attitudes towards Commerce

One of the most widely discussed economic theories outside the economics department is *The Protestant Ethic and the Spirit of Capitalism* written by Max Weber in 1904. His book illustrated how religion strongly shapes a society's character traits, which in turn play a huge role in determining its economic success. Weber noticed a stark contrast between the economic fortunes of Germany's Protestants, who showed "a special tendency to develop economic rationalism" compared to its Catholics (Weber 1905/1960, p. 7). Weber hit upon an insightful correlation, that certain religions, especially early Protestant sects, shared beliefs about life and work that made them extremely well adapted to modern capitalism. A spirit of progress and a love of hard work for its own sake combined with a focus on profit over pleasure were traits that characterize most successful entrepreneurs.

Economists have vacillated between a complete rejection of Weber's theory to a general acknowledgement that religious ideas can be important causes for the development of new economic institutions (Samuelsson 1973, p. 137-149; Landes 1969, p. 22-24). Those who do embrace Weber tend to be anglophile economic historians who emphasize the unique character of Britain in fostering its inventive success. In *The Wealth and Poverty of Nations* David Landes (1998, p. 516) concludes: "If we are to learn anything from the history of economic development, it is that culture makes all the difference. (Here Max Weber was right on.)". But then, where most economists disagree with the father of sociology is that it is very unclear that Protestantism actually "causes" entrepreneurial behavior. A disproportionate amount of economic success is sometimes seen among cultural and religious minorities, but a common correlation does not say anything about causation. As noted above, the English Enlightenment coexisted quite comfortably with Protestantism (much more than France), likely because the religion was pliable (or weak) enough to be reconciled with modern ideas of science and industry.

Britain provided a unique response to her religious turmoil and fanatical strife that stoked the civil war and the axing of Charles in 1649. In stark contrast to Catholic France in the late seventeenth century, England repudiated old militancy for modern civility. Fortunately for this story, a belief was born in the aftermath of the Wars of Religion; that commerce that would destroy sectarianism uniting those whose creeds previously tore them apart. Voltaire (cited in Porter 2000, p. 20-21) actually witnessed this:

> *Take a view of the* Royal Exchange *in* London*, a place more venerable than many courts of justice, where the representatives of all nations meet for the benefit of mankind. There the Jew, the Mahometan, and the Christian transact together as tho' they all profess'd the same religion, and give the name of Infidel to none but bankrupts. There the Presbyterian confides in the Anabaptist, and the Churchman depends on the Quaker's word. And all are satisfied.*

Dissenting Academies

Commerce did grease the wheels of religious tolerance in Britain, but it was not always the rosy picture painted by Voltaire. A clear view can be made on how religious tolerance affected the fate of the steam engine by contrasting the experiences of two of its inventors, Denis Papin and Thomas Newcomen. Both belonged to dissenting religious sects and experienced persecution because of their beliefs, but the degree of oppression differed drastically in Papin's France compared with Newcomen's England.

Newcomen's early life is hazy, as his name does not appear in official records since his family was Baptist. Dissenting religions such as Baptists, Presbyterians and Quakers were barred from attending the two English universities (Oxford and Cambridge), but Charles II granted them the freedom to establish "dissenting academies" or attend university in Glasgow or Edinburgh in Scotland. This was another example of unintended consequences benefiting Britain, as the academies retained the classical education of Oxbridge, but also were unrestrained in teaching the latest in scientific thought and methods. The religious restriction also led some of Britain's most ambitious and practical young men into practical apprenticeships after a general education that ensured these skilled artisans also were literate.

Another strange Restoration era restriction prohibited non-conformist pastors from preaching within five miles of their hometown. This forced the Oxford-educated Baptist preacher, John Flavel, to move from Dartmouth, bringing him closer to Newcomen. Before his apprenticeship as an ironmonger, Newcomen greatly benefited from the bizarre law as it put him in contact with the pastor, who likely taught him some mathematics in between Sunday services. It is also interesting that he met his partner, John Calley who he gave credit for getting their steam engine to actually work, in a secret Baptist community service, since the law forbade religious gatherings of more than five people. Lastly, the Dartsmouth Baptist community, as well as other dissenting communities, organized secret community banks, which actually funded Newcomen's first experiments on the steam engine (Rosen 2010, p. 50).

Another example where religious persecution in England actually contributed to the success of an individual inventor was Abraham Darby, who was previously introduced for his development of a coke-fueled blast furnace. Darby was part of the Society of Friends, or Quakers, which was one of the later religions to break away from the established Church of England during and after the English Civil War (1642-1651). The new religion gained a considerable following even after being labelled blasphemous with its unconventional ideas such as their pacifism and opposition to superstitious oaths. They experienced tremendous official persecution, being forced to swear an oath of allegiance to the king (the Quaker Act), but were no longer deemed criminals after the Toleration Act of 1689. Again, since they were barred from academics, ambitious Quakers went into manufacturing or commerce. They quickly gained a reputation for their integrity in setting a fair price for their quality goods. This stands in stark contrast with the *homo economicus* view of an unscrupulous, money-grabbing entrepreneur and emphasizes the importance of trust for innovators and entrepreneurs. Darby also profited from his Quaker connection after moving to Bristol in his early twenties, where he was embraced by the community who he joined in business (King 2014, p. 28-31). This is a testament to the age-old tendency for persecuted minorities to take care of their own.

Discussion: The Mystery Revealed

Comparison and Evaluation of the Fundamental Institutions

The comparison of the institutions surrounding the invention and development of the steam engine brought to light a number of potential causes to explain why it was predominantly based in Britain and not France. Before evaluating the variables and their potential causality, it is important to revisit the theories of invention in order to get a clear picture of how innovation actually occurs. The three sources of invention are: 1) the "heroic inventor" or "great man"; 2) a response to the scientific or ideological environment that stimulates technological progress; and 3) socially determined innovation based on social or economic needs or demands.

Taking the steam engine as an example, James Watt exemplifies all three sources, including the "heroic inventor" with his flash of insight and the countless other inventions he authored. He did so in response to a society that valued engineering and mechanical skills and in a university setting where access to scientific knowledge was abundant. Lastly, it was clearly a socially determined innovation as Matthew Boulton and other investors in Watt's separate condenser engine perceived an economic demand in Cornwall's mines and industrial factories.

One sees a similar pattern in the first three inventors of the steam engine. Although they lived within the same environment and timeframe, differing theories best fit each individual case. Papin's steam engine falls squarely into the "response" camp, as it was the culmination of many years of scientific inquiry and experimentation. Savery's engine could be seen as inevitable given the ever-increasing industry demand for mine drainage and the relatively low cost of coal fuel relative to charcoal and human labor. He was also heavily influenced by market incentives, which is apparent from his marketing prospectus. Lastly, as the superior Newcomen engine relied less on science and more on persistent trial-and-error engineering (like the fluke accident that led to the water jet condenser), it could be considered the product of a "great man".

Each of these theories on their own suffer from unilaterally explaining the origins of invention. However, a synthesized theory that allows for all three sources, but with varying magnitudes of importance, provides the best model for interpreting the complex reality of innovation.

With this appropriate theoretical foundation, the relevant institutions surrounding the invention of the steam engine can now be evaluated. Based on the scholarship surrounding the related question of why most of the Industrial Revolution's decisive inventions originated in Britain, a selection of potentially causal variables has been compared between Britain and France. The invention itself was the result of a "perfect storm" of several factors, where some variables were *necessary conditions*, while others were merely *contributing factors* that varied in their significance. This distinction, used prevalently in the insurance world, is simple and intuitive. Necessary conditions produce a root causal effect; without the condition, the effect would not be present. Contributing factors influence the effect by increasing its likelihood or accelerating the effect. The following evaluation takes into account both the degree of importance of each factor, as well as the national and institutional differences between the two countries.

Necessary Conditions (Causal Factors)

Science

A direct link can be traced from science to the steam engine. It is highly improbable that the steam engine could have been conceived, let alone invented without the century-long scientific effort. Understanding the main working principles of steam and its ability to direct water or a wheel, was the first necessary development. Then, the experiments that confirmed the existence of vacuum opened the door to understand how atmospheric pressure could push a piston. It is disputed whether Savery or Newcomen[28] had a scientific understanding of how their engines worked, but their designs were plainly defined by the purely scientific breakthroughs that preceded them. Savery's dependence on science is even more clear-cut since he blatantly incorporated elements from prior inventions into his engine[29]. This paper has also emphasized the role science played in advancing James Watt's experiments with steam technology. In a multivariate regression, science would be an extremely significant causal factor in the invention of the steam engine. Yet, because the level of scientific knowledge in France was equal, if not more advanced, there must be another necessary condition for the invention.

It has been noted that Britain emphasized a more practical Baconian scientific program, while France followed the theoretical Cartesian course. The difference in the application of scientific knowledge in England and France illustrates how "the factors that affect the demand for science are overwhelmingly more important than factors affecting its supply" (Rosenberg 1976, p. 129). Marx's historical materialism is apparent here in its emphasis that science advances when there is a social need for it. Indeed, his intellectual partner, Fredrick Engels (1883/1940, p. 187) wrote "the origin and development of the sciences has been determined by production". While it is too much of a stretch to claim that all scientific pursuit is motivated by the needs of industry[30], it is a helpful concept when analyzing the intense English interest in the science of steam and vacuum immediately preceding the steam engine's invention compared to France's relative disinterest at the time.

Resource Endowments

It is not a coincidence that Britain dominated in technologies that played to its unique natural resource endowments, including its rich coal deposits in the midst of a relatively high wage economy (Allen 2009, p. 267-269). Britain had developed a booming coal market, which provided the heat for the growing London populace, and was beginning to develop coke-smelting technologies that would only increase its demand. As coal mining went deeper into the ground, it desperately needed technology that would solve the water drainage problem faced by British collieries (coalmines). The French coal mining industry showed little interest

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[28] Newcomen would have been exposed to numerous Huguenots who sought refuge in his hometown, bringing with them Papin's publications in Latin and French. In the 1797 *Encyclopedia Britannica* entry on the "steam engine", Dr. John Robison (1797, p. 743-744) noted a connection between Newcomen and Robert Hooke, who would have surely given an explanation of his and Papin's findings. However, this allegation is suspect given the numerous factual mistakes prevalent in the article and the absence of any written correspondence between the two.

[29] Savery (1702, p. 8) himself referred to old devices that were "short of performing what they pretended to" in his *Miner's Friend* book/advertisement.

[30] In his defense, Engels never finished his *Dialects of Nature*, so the overemphasis on the demand-induced incentives to science might have been toned down or more nuanced in a completed work.

in the steam engine until the drastically superior high-pressure engines were introduced in the nineteenth century, justifying the use of steam power given the high price of coal in France. This means that a French version of Savery or Newcomen in the eighteenth century would have invested at least a decade in concentrated R&D without any prospect of commercial gain, since there was no market for the device in France and patents did not cross international borders.

The slow diffusion pattern of the steam engine in France provides clues to the potential demand an inventor might face, but a comparable counter-factual exercise for Britain is impossible since it was the original home of the steam engine. In other words, the history and economics of the steam engine can clearly illustrate why the steam engine originated in Britain and not France, but it is more difficult to deduce that the steam engine was invented in Britain *because* of its natural resource endowments.

A large market and a clear economic need for the invention would certainly induce its invention. However, the argument has been made that China, Russia and North America all have a fortuitous presence of abundant coal, but failed to make any advances towards steam technology in mining. This thesis has already provided ample evidence that access to relevant scientific knowledge was critical for the invention. This knowledge was not widely available outside of a few locations in Western Europe. In addition, only richer countries with large markets can undertake the high risk, but high return nature of new technologies. Lastly, the inability of developing countries to generate innovations that favor their factor endowments of abundant labor, but scare capital illustrates that England's natural resource endowment was not enough to spur the invention of the steam engine. It also required an institutional environment amiable to the development of technical skills and innovation.

An Inventive Class of Skilled Artisans

While the mere existence of coalmines clearly is not sufficient to incite steam technology, the already thriving market for coal unquestionably focused the creative energies and attention of potential inventors. As noted previously, the mining industry encouraged three-quarters of patents granted in England prior to 1700 and 15 percent were for drainage innovations alone (Wallace 1982, p. 33).

Quantitative studies that seek to provide detailed characteristics of the great inventors of the eighteenth century have established that they were not an elite few heroic scientists, but rather a very small[31] group of highly skilled craftsmen and mechanics. The usual route to expertise was through seven-year apprenticeships, which would result in nearly twice the amount needed for "expert performance[32]". The workforce that turned ideas into reality and continually improved existing machines is what gave Britain its edge. British innovators quickly adopted a scientific methodology of discovery through painstaking experimentation and measurement. They also exploited useful knowledge promoted by the Royal Society and created cooperative networks across industries. These synergies reveal the fortuitous nature

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[31] Perhaps no more than 5% of the total workforce (Mokyr and Voth 2008)

[32] "Expert performance" is the extremely controversial idea proposed by Anders Ericsson that ten thousand hours is what separates the professionals from the rest.

of British endowments in iron, coal and water transportation, given the effects those industries had on driving the manufacturing and transportation sectors.

While the *idea* of the steam engine would be unthinkable without relevant scientific knowledge, its *implementation* would be unattainable without sufficient engineering and mechanical skills. In this light, Britain's inventive class was a necessary, but not a sufficient condition for the invention of the steam engine. France also harnessed its engineers, but its largely agricultural base did not supply nearly as many as Britain and only deployed them in areas deemed strategic by the state or the military. French attempts at replicating British invention consistently failed as their engineers struggled with condensing decades of mechanical experience and adapting already customized technologies to French conditions. Mathias (1979, p. 25) notes the technical problems in diffusing skills where economic incentives are ignored, such as military or other public sector needs. Given time though, France's engineers would have likely succeeded in improving Papin's piston-driven steam engine if its coal market was as large as Britain. This speculation is based on the later success of French engineers during the Napoleonic wars in developing innovative mining and surveying techniques once they controlled mines throughout Europe (Cameron 1961, p. 44).

Contributing Factors

Economic Institutions

The high percentage of patents within Britain's mining industry would lead one to believe that the patent system provided an incentive to innovate. Evidence from the history of the steam engine as well as other studies have shown that while patents may provide hope of monopoly profits, they can also block or slow the process of innovation. The patent itself could also be seen as a symbol or proof of a deeper societal respect for property rights[33]. Reminiscent of the argument that an eager market induces innovation by providing an economic return on one's R&D investment, property rights would serve the same purpose by protecting that commercial gain. Possibly more important than a patent to a potential inventor is the ability to finance one's R&D efforts. Without the ability to support the material needed to experiment, let alone one's livelihood, a potential invention will remain a fantasy.

Economic institutions that assist financing and protect property rights certainly played a contributing role in the invention of the steam engine, albeit far less than resource endowments and access to scientific knowledge. However, the evidence is much less clear that they determined the location of the invention. Inventors on either side of the Channel faced slightly different economic institutions, where the British focused on market-driven incentives in the form of patents, while the French emphasized state-driven rewards to carefully evaluated inventions. The key was that both governments shared the goal of technological advancement. It has been shown the countries were equally successful in promoting innovation and industries, but only to the extent that they could be economically justified. This is especially apparent in the case of France, which engaged in industrial

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[33] Ancient Rome provided imperial grants for the exclusive right to produce a particular good, but property rights were still dubious. This is illustrated by the story told contemporaneously by Pliny the Elder of a glazier who invented an "unbreakable" glass cup. Emperor Tiberius had him behead in order to preserve the value of gold and silver.

espionage in order to rapidly adopt British technologies. These efforts consistently failed where the technologies were biased to Britain and not France's factor endowments.

Social, Political and Religious Institutions

Britain and France also exhibited very distinct environments in the political, religious and social sphere. However tempting it is to completely ascribe Britain's success and France's failure to these institutions, this thesis has demonstrated that a careful analysis of *actual outcomes* is more important than *apparent differences*. It is supported by extensive empirical work that shows France growing respectably for most of the eighteenth century (Marczewski 1961). In fact, France's "medieval" institutions as characterized by North and Thomas (1973) remained largely the same in the seventeenth and eighteenth century, yet the French economy experienced an impressive growth rate more rapid than England (Crouzet 1990, p. 73). Some scholars have also called attention to the *lack of* differences between England and France during this time, asserting, "chance played a role in the timing and speed of Britain's initial surge" (Voth and Voightländer 2006, p. 320-321).

Britain's Anglican Church contrasted with France's Catholicism illuminates subtle differences in how they treated science and commerce, with Britain taking a more positive approach. Britain's relatively new state religion accepted the new sciences more easily than Catholicism and its crown valued commerce for its unifying power. This gave a small, but unremarkable advantage to Britain concerning the invention of the steam engine. However, an even greater distinction was in how they treated their religious minorities. While the Huguenots were expelled from France in the late seventeenth century, British non-conformists were allowed their own schools and banks, creating valuable community support for inventors.

Political institutions could affect inventive activity either through the economic institutions they encourage or their capacity to foster human capital. Economic historians have pinpointed the Glorious Revolution of 1688 as Britain's turning point in the protection of property rights, arguing that the timing explains the boom in subsequent inventive activity. However, this view is not supported by the evidence that shows how few inventors in the eighteenth century collected substantial material rewards. The historical record of many inventions reveals the large role that non-monetary incentives and individual genius seems to have played. In addition, many of the key breakthroughs of the early Industrial Revolution were not an original idea or blueprint, but rather new ways of adapting or improving existing technologies.

Conclusion

The invention of the steam engine finally occurred almost one hundred years after initial experiments indicated the power of the vacuum in raising water. It also occurred nearly one hundred years after the colliery owners, who first put the invention to use, noted the need for such technology to drain the mines. It took another seventy-five years before a major innovation would make them cost-effective for use away from coalmines and an additional seventy-five years before their use overtook the competing alternative energy of waterpower. Inventions can sometimes seem like new biological species created under just the right evolutionary conditions. It is easy to trace the path to their emergence after the fact, but both biology and invention show a baffling indeterminacy in history.

Finding just the specific conditions that foster innovation has proven elusive, since many examples do not follow the conventional economic wisdom. Society has always sought medical advances to improve the lives of the population, but they did not significantly develop until the twentieth century, when science ushered in effective treatments. There was no market for manned flight when the French Montgolfier brothers invented hot air ballooning in 1783 or when the American Wright brothers patented “new and useful Improvements in Flying Machines” in 1903. In addition, the examples of Abraham Darby’s coke smelting technique and James Watt’s separate condenser illustrate how macro-inventions result from random strokes of luck with some genius mixed in. This paper illustrates how important timing is for inventions as they are dependent on numerous necessary conditions occurring simultaneously. The factors for success include having adequate materials and skills to construct the technology, cost-effective inputs, and power structures (influential institutions) that view the invention either positively or benignly at the very least.

Britain was the first country to generate the perfect storm of conditions that would adopt steam technology, initially because of the large coal market and demand for water pump technology. However, a coalmine and a societal need does not always induce invention. British ingenuity focused on the problem was also needed. She combined her raw materials, equipment and know-how to generate inventions that fit perfectly with her natural resources endowment. It was not purely geology, but Britain’s human capital in coal and metalworking techniques as well as the ever-alert entrepreneurs that were able to exploit what was in the ground.

This thesis shares the explanations for British success of a few prominent economic historians, notably Robert Allen (2009, p. 2) who argues, “the Industrial Revolution…was invented in Britain in the 18th century because it paid to invent it there”. His focus has been on their unusual price and wage structure, while this study has focused on the very cheap price of coal that sustained the early inefficient engines. Also, Joel Mokyr (2009, p. 122) explains Britain’s early lead in the Industrial Revolution as “it was able to take advantage of its endowment of human and physical resources thanks to the great synergy of the Enlightenment: the combination of the Baconian program in useful knowledge and the recognition that better institutions created better incentives”. Rather than assume them mutually exclusive arguments, the example of the steam engine illustrates that they are complementary.

While the British showed a unique knack for finding technological solutions and exploiting ever-widening markets, they did not possess a monopoly on discovery and invention. France often displayed its creative force in meeting the needs and opportunities present in its economy. French invention was often geared towards luxury goods and they took an early lead in perfecting silk manufacturing, despite Britain's persistent efforts to develop her own industry. French inventors simplified and standardized silk manufacturing culminating in the revolutionary Jacquard loom, a precursor to computer punch cards, it allowed the mass-production of complex designs. The French often employed their resourcefulness in the service of the state, as when Napoleon successfully created a sugar beet industry from scratch through special schools and subsidies after a sugar shortage due to the British blockage and the Haitian Revolution affected the population. The *Académie des Sciences* offered a generous prize in 1783 for a method to produce alkali, which is a vital chemical in the glass, soap and paper industries, from sea salt. Nicolas Leblanc eventually succeeded, taking out a patent and opening his own production plant. Unfortunately, he never did receive the prize money, as the French revolutionary government took power and confiscated his factory[34] (Gillispie 2004, p. 415).

Comparing the inventions originating in France versus Britain reveals their very different nature of innovation. Britain's inventions had a much wider economic impact given their much larger demand. This is partly a result of Britain's greater focus on *market-driven* innovations, while the French government achieved its strategic goals through "*state-induced*" invention. Also, the British were tremendously lucky in that steam and iron technologies became a strategic sector with tremendous ramifications given their multiple uses within the larger economy. In an organic fashion, each development fed off the other, where the whole became greater than the sum of its parts.

As Britain dominated in technologies associated with fossil fuels in the First Industrial Revolution, France later took the lead in scientific- intense industries, such as chemical, papermaking and glass (Musson and Robinson 1969, p. 61, 81, 260). This is also supported by Mathias' observation that "the closer technology depended upon formal scientific training at the end of the eighteenth century, the greater the influence of France as the mentor of Europe" (Mathias 1979, p. 22-23). If by some twist of geologic fate, the British Isles had not risen from the ocean or had been deprived of her rich coal and iron deposits, France or possibly Germany would have given birth to an Industrial Revolution, although a bit later and with a very different pattern, as shown by their leadership in the Second Industrial Revolution.

The Industrial Revolution that began in Britain in the eighteenth century is the ultimate mystery novel. Just as in Agatha Christie's *Murder on the Orient Express*, where Inspector Hercule Poirot determines that all the passengers on the train are guilty in the murder, the causes of Britain's inventive revolution are many. Settling on just one causal factor limits valuable insights found in the complex environment of economic history. The Industrial Revolution, and especially its inventions, are excellent case studies from which we can learn why economies grow. They teach us how the miracles of technology and efficient markets and institutions can break the shackles of poverty.

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[34] Napoleon did return the plant to Leblanc, but with no money to run it, he committed suicide.

This study has shown that Britain's unique natural resource endowments combined with her skilled artisans focused on mining and machinery, gave her a much greater probability of inventing the steam engine than France, even with the uncertainty and unknowable factors involved. This is not to say that Crafts (1977/1985) was wrong that the Industrial Revolution *as a whole* taking place in England was the result of a stochastic process. However, *in the case of the steam engine*, the probability of it first occurring in Britain was close to inevitable.

Figure 19 - Painting of a Colliery (1790)

Post-Script: Steam Power, the Industrial Revolution and Economic Growth

At the conclusion of some an engaging story in popular cinema or television, the viewer is sometimes rewarded with a post-script that summarizes what happened after the credits are shown. Here is the story after the story:

The Engine that Powered the Industrial Age

This thesis brought the account of steam power up to James Watt and the end of his patent in 1800, but the saga did not stop there. Steam power in the eighteenth century showed very few clues that it would revolutionize the world through its application in factories and transportation. It did not overtake waterpower as a dominate source of energy until 1830. Indeed, the steam engine contributed very little to productivity growth until one hundred years after its invention and peaked at 0.38% per year from 1850 to 1870 (Crafts 2004, p. 22). Things gradually picked up steam as a number of high-pressure and compound engines were adopted. These would result in smaller, faster and more powerful engines that would become the dominate power source in manufacturing until the early twentieth century.

Table 4 - Sources of Horsepower, 1760-1907 (Kanefsky 1979, p. 338)

	1760	1800	1830	1870	1907
Steam	5,000	35,000	160,000	2,060,000	9,659,000
Water	70,000	120,000	160,000	230,000	178,000
Wind	10,000	15,000	20,000	10,000	5,000
Total	***85,000***	***170,000***	***350,000***	***2,300,000***	***9,842,000***

The steam engine acted as an agent of change that far outstripped anything the inventors could have ever imagined. The "Steam Age" really got going when engines were adapted to power locomotives and boats, literally changing the geographic and genetic landscape of the Western world. Nicolas Cugnot would have been proud to see the numerous steam-powered passenger vehicles driving around Paris in the late nineteenth century. The final evolution was to steam turbines, which are today the source of 90% of electric power in the United States.

The Industrial Revolution in Britain and France

It is tempting to believe, given Britain's seemly modern political and economic institutions combined with its comparative advantage in industry that the British would have lived happily ever after. One could also imagine an economic tragedy in France due to its highly promising, but ultimately disastrous Revolution, with its Reign of Terror, numerous foreign wars and the failed Republiqué. The Napoleonic Empire was short-lived and ended with the Restoration of the monarchy, albeit with much less power than under the Ancien Régime. In the 1815 aftermath, France was saddled with paying onerous reparations, plus the "privilege" of footing the sizable room and board bill for hundreds of thousands of multinational occupying soldiers.

Despite the tremendous diversion of resources, France finally began its industrialization by capitalizing on British improvements to the now fuel-efficient steam engines. This, together with drastic enhancements to the transportation infrastructure, coal mining and iron works were finally feasible in France. For instance, the famous state-sponsored iron works at Le Creusot failed during the eighteenth century, but blossomed again in the nineteenth century when it gave birth to the French locomotive and weapons industries. In 1850 alone, France issued 2,272 patents, which was more than the U.S. and Britain combined for that year. Patrick O'Brien and Caglar Keyder (1978) showed that the industrialization of France was no less successful than England, but "simply took place in a different legal, political and cultural tradition". They called the transition "more humane and no less efficient" than the British experience. The disparate paths of Britain and France going into the twentieth century led to similar economic results, but while France lagged in GDP per capita until the 1960s, it experienced lower levels of income inequality and as the French would argue, they enjoyed a much greater "joie de vivre".

Britain's process was less dramatic, with a conservative parliament handling most reforms under a benevolent constitutional monarchy exemplified by the moral compass of Queen Victoria. However, by 1914, even with her staid political process, Britain was demoted as the world leader to only one of many economic powers. This confirms the tendency of economic leadership towards transience, as institutions can become complacent in adapting to changing conditions.

The Long and Winding Road of Economic Growth

This thesis underscores the dangers of assuming there is only one recipe for economic growth and technological advancement that countries can easily emulate. Hindsight bias can lead to precarious reinterpretations of history by assuming all prior conditions led to the inevitable outcome. Despite their contrasting formal institutions, both Britain and France experienced modern economic growth during the nineteenth century, which was driven by technology and incentivized through both the market and the state. Instead of focusing on how particular political or economic systems led to modern economic growth, more emphasis should be placed on how/why countries are successful in minimizing rent-seeking activity.

Although glorified by many economic historians, eighteenth-century Britain struggled just as much as France did in constraining redistributive activities (Mokyr 2009, p. 24). Power structures in the state and market intent on retaining power or profits both imposed numerous restrictions on the population that contributed the most to society – its innovators. Self-serving practices and institutions detrimental to economic growth came in all shapes and flavors, including the French "privilège" or the tight regulation of British apprenticeships. An ideal economy would democratize invention and naturally develop institutions that provide the right incentives for the financing and sale of innovation.

Fortunately, in the nineteenth century, after all the countless wars fought between Britain and France, an economic competition developed wherein their populations began to appreciate the power of the free market. Just as rent-seeking institutions took various forms, so did the processes to change and update institutions. France experienced many revolutions and experimented with radical ideas, which sometimes served to remove stubborn institutional constraints or obstacles. The French often emulated the British example, but also followed its own path, occasionally through violent revolution. All these institutional changes led France to its current unique brand of free-market social capitalism.

The path of modern economic growth can be winding and sometimes filled with rocks, thorns and glass that hurt individuals[35]. There were wrenching changes in lives as many hand artisans lost their livelihood, factory work became dismal and unsafe, and squalor became a way of life for those in the bulging cities. As Arnold Toynbee (1884, p. 226) put it in his *Lectures on the Industrial Revolution in England*, society was "suddenly broken in pieces by the mighty blow of the steam engine and the power loom". Ultimately, as inventions were generated and innovations applied, productivity (output per hour of work) rose and the fruits of their labor were eventually granted in growing incomes. Ironically, the opportunity to earn more actually provoked discontent among many workers as they protested unfair conditions and income inequality. It could be argued that economic growth and its resulting discontent also spurred political reform that would level and broaden opportunity.

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[35] Not cool Robert Frost!

Works Cited

Acemoglu, Daron, and James A. Robinson. *Why Nations Fail: The Origins of Power, Prosperity, and Poverty*. New York: Crown, 2012. Print.

Acemoglu, Daron. *Introduction to Modern Economic Growth*. Princeton: Princeton UP, 2009. Print.

Acemoglu, Daron, Simon Johnson, and James A. Robinson. "Chapter 6 Institutions as a Fundamental Cause of Long-Run Growth." *Handbook of Economic Growth* (2005): 385-472. Web.

Aeppel, Timothy. "Economists Debate: Has All the Important Stuff Already Been Invented?" *The Wall Street Journal* 15 June 2014: n. pag. 15 June 2014. Web. 2 May 2016.

Albouy, David Y. "The Colonial Origins of Comparative Development: An Empirical Investigation: Comment." *The American Economic Review* 102.6 (2012): 3059-076. *JSTOR*. Web. 15 May 2016.

Allen, Robert C. "Collective Invention." *Journal of Economic Behavior & Organization* 4.1 (1983): 1-24. Web.

Allen, Robert C. *The British Industrial Revolution in Global Perspective*. Cambridge: Cambridge UP, 2009. Print.

Allen, Robert C. "Why the Industrial Revolution Was British: Commerce, Induced Invention, and the Scientific Revolution1." *The Economic History Review* 64.2 (2011): 357-84. Web.

Angrist, Joshua D. "Lifetime Earnings and the Vietnam Era Draft Lottery: Evidence from Social Security Administrative Records." *The American Economic Review* 80.5 (1990): 1284-286. *JSTOR*. Web. 15 May 2016.

Aoki, Masahiko. "Information and Governance in the Silicon Valley Model." *Theoretical and Empirical Perspectives Corporate Governance* (1999): 169-200. Print.

Arago, F. *Historical Eloge of James Watt*. Trans. James Patrick Muirhead. London: J. Murray, 1839. Print.

Ashton, T. S. *Iron and Steel in the Industrial Revolution*. Manchester, Eng.: Manchester UP, 1951. Print.

Bagust, Harold. *Sir Marc Brunel: The Greater Genius?* Stroud: Tempus, 2005. Print.

Bagwell, Philip S., and Peter J. Lyth. *Transport in Britain from Canal Lock to Gridlock*. London: Hambledon and London, 2002. Print.

Ballot, Charles. *L'Introduction Du Machinisme Dans L'industrie Française*. Genéve: Slatkine, 1978. Print.

Becker, Gary Stanley. *Human Capital: A Theoretical and Empirical Analysis*. Chicago: U of Chicago, 1993. Print.

Bell, Arthur. *Christian Huygens and the Development of Science in the Seventeenth Century*. London: Bell, 2008. Print.

Berg, Maxine, and Kristine Bruland, eds. *Technological Revolutions in Europe: Historical Perspectives*. Chelten, UK: Edward Elgar, 1998. Print.

Bernstein, Ruth, and Stephen Bernstein. *Biology, the Study of Life*. New York: Harcourt Brace Jovanovich, 1982. Print.

Bénabou, Roland, Davide Ticchi, and Andrea Vindigni. "Religion and Innovation." *American Economic Review* 105.5 (2015): 346-51. Web.

Boldizzoni, Francesco. *The Poverty of Clio: Resurrecting Economic History*. Princeton, NJ: Princeton UP, 2011. Print.

Boldrin, Michele, and David K. Levine. *Against Intellectual Monopoly*. New York: Cambridge UP, 2008. Print.

Brockliss, L. W.B. "The Scientific Revolution in France." *The Scientific Revolution in National Context*. Ed. Roy Porter and Mikuláš Teich. Cambridge: Cambridge UP, 1992. 55-89. Print.

Burke, James. *Connections*. Boston: Little, Brown, 1978. Print.

Burton, Anthony, and Jennifer Tann. *Matthew Boulton: Industry's Great Innovator*. Stroud: History, 2012. Print.

Cameron, Rondo E. *France and the Economic Development of Europe, 1800-1914; Conquests of Peace and Seeds of War*. Princeton, NJ: Princeton UP, 1961. Print.

Cardwell, D. S. L. *Steam Power in the Eighteenth Century: A Case Study in the Application of Science*. London: Sheed and Ward, 1963. Print.

Cardwell, D. S. L. *The Fontana History of Technology*. London: Fontana, 1994. Print.

Carpenter, Audrey T. *John Theophilus Desaguliers: A Natural Philosopher, Engineer and Freemason in Newtonian England*. London: Continuum International Pub. Group, 2011. Print.

Cerf, Alain A. *Nicolas Cugnot and the Chariot of Fire*. Pinellas Park, FL: Tampa Bay Automobile Museum, 2010. Print.

Chaptal, Jean-Antoine-Claude. *De L'industrie Française*. Comp. Louis Bergeron. Paris: Imprimerie Nationale Ed., 1993. Print.

Chen, Keith. "Could Your Language Affect Your Ability to save Money?" TED Global. Edinburgh. June 2012. *TED.com*. Web. 15 May 2016.

"Churchill Voted Greatest Briton." *BBC News World Edition*. BBC, 24 Nov. 2002. Web. 15 May 2016.

Cipolla, Carlo M. "The Diffusion of Innovations in Early Modern Europe." *Comparative Studies in Society and History* 14.01 (1972): 46-52. Print.

Clark, C. F. G., and Dud Dudley. *The Curiosities of Dudley and the Black Country, from 1800 to 1860: Also an Account of the Trials and Sufferings of Dud Dudley with His Metallum Martis, the First Artificer in Iron, Made with Pit Coale and Sea Coale, in 1618*. Birmingham: Buckler Bros., 1881. Print.

Clark, Gregory. "The Political Foundations of Modern Economic Growth: England, 1540-1800." *Journal of Interdisciplinary History* 26.4 (1996): 563-88. Web.

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

Clout, Hugh D. *Themes in the Historical Geography of France*. London: Academic, 1977. Print.

Conlon, Thomas. *Thinking about Nothing: Otto Von Guericke and the Magdeburg Experiments on the Vacuum*. London: Saint Austin, 2011. Print.

Cooke, John. *Transactions of the Royal Irish Academy. ... Volume 3 of 7*. Vol. 3. S.l.: Gale Ecco, 2010. Print.

Cooper, Carolyn C. "The Portsmouth System of Manufacture." *Technology and Culture* 25.2 (1984): 182-225. Print.

Cowan, Brian William. *The Social Life of Coffee: The Emergence of the British Coffeehouse*. New Haven: Yale UP, 2005. Print.

Cowen, Richard. "Coal." *Essays on Geology, History, and People,*. UC Davis, 13 Mar. 2013. Web. 12 May 2016.

Crafts, Nicholas. "Exogenous or Endogenous Growth? The Industrial Revolution Reconsidered." *The Journal of Economic History* 55.04 (1995): 745-72. Web.

Crafts, Nicholas. "Industrial Revolution in England and France: Some Thoughts on the Question "Why Was England First." *The Economics of the Industrial Revolution*. Ed. Joel Mokyr. Totowa, NJ: Rowman & Allanheld, 1985. 119-36. Print.

Crafts, Nicholas, and Mark Thomas. "Comparative Advantage in UK Manufacturing Trade, 1910-1935." *The Economic Journal* 96.383 (1986): 629-45. Print.

Cressy, David. *Literacy and the Social Order: Reading and Writing in Tudor and Stuart England*. Cambridge: Cambridge UP, 1980. Print.

Crouzet, Francois. "England and France in the Eighteenth Century: A Comparative Analysis of Two Economic Growths." *The Causes of the Industrial Revolution in England*. Ed. R. M. Hartwell. London: Methuen, 1967. N. pag. Print.

Crouzet, François. *The First Industrialists: The Problem of Origins*. Cambridge: Cambridge UP, 1985. Print.

Crouzet, François. *Britain Ascendant: Comparative Studies in Franco-British Economic History*. Cambridge: Cambridge UP, 1990. Print.

Crouzet, François. *A History of the European Economy: 1000-2000*. Charlottesville: U of Virginia, 2001. Print.

Cugnot, Nicolas-Joseph. *Éléments De L'art Militaire Ancien Et Moderne, Par M. Cugnot,..* Paris: Vincent, 1766. Print.

David, Jacques-Louis. *Portrait of Antoine-Laurent Lavoisier and His Wife*. Ca. 1788. N.p.

David, Paul A. "Path Dependence, Its Critics and the Quest for "historical Economics"" *Evolution and Path Dependence in Economic Ideas: Past and Present*. Ed. Pierre Garrouste. Comp. Stavros Ioannides. Cheltenham, UK: Edward Elgar, 2001. 15-40. Print.

Davis, Ralph. *The Rise of the Atlantic Economies*. Ithaca, NY: Cornell UP, 1973. Print.

Dawson, Frank. *John Wilkinson: King of the Ironmasters*. Ed. David Lake. Stroud: History, 2011. Print.

Derry, T. K., and T. I. Williams. *A Short History of Technology: From the Earliest times to A.D. 1900*. Oxford: Oxford UP, 1960. Print.

Desaguliers, John Theophilus. *A Course of Experimental Philosophy*. Vol. 2. London: W. Innys, 1744. Print.

Dickinson, H. W. *James Watt, Craftsman & Engineer*. New York: A.M. Kelley, 1936. Print.

Dickinson, H. W. *A Short History of the Steam Engine*. N.p.: Cambridge UP, 2011. Print.

Dudley, Dud. *Dud Dudley's Metallum Martis: Or, Iron Made with Pit-coale, Sea-coale &c. and with the Same Fuell to Melt and Fine Imperfect Mettals, and Refine Perfect Mettals*. London: T.M. for the Author, 1665. Print.

Dunham, Arthur Louis. *The Industrial Revolution in France, 1815-1848*. New York: Exposition, 1955. Print.

Dutton, H. I. *The Patent System and Inventive Activity during the Industrial Revolution, 1750-1852*. Manchester: Manchester UP, 1984. Print.

Eagle, Cassandra T., and Jennifer Sloan. "Marie Anne Paulze Lavoisier: The Mother of Modern Chemistry." *Chem. Educator The Chemical Educator* 3.5 (1998): 1-18. Web.

"Economic History Is Dead; Long Live Economic History?" *Economist* 7 Apr. 2015: n. pag. Print.

Edward, Somerset. *The Marquis of Worcester's Century of Inventions to Which Is Added, an Appendix; Containing an Historical Account of the Fire-engine for Raising Water; Which Invention Originated from the above Work. By John Buddle*. Newcastle: T. Slack and G. Robinson Pater-Noster-Row, 1778. Print.

Engels, Friedrich. *Dialectics of Nature*. Trans. C. P. Dutt. Comp. J. B. S. Haldane. New York: International, 1940. Print.

Enos, John L. *Petroleum Progress and Profits; a History of Process Innovation*. Cambridge: M.I.T., 1962. Print.

Epstein, Stephan R. *Freedom and Growth: The Rise of States and Markets in Europe, 1300-1750*. London: Routledge, 2000. Print.

Epstein, Stephan R. , and M. Prak. *Guilds, Innovation and the European Economy, 1400–1800*. N.p.: Cambridge UP, 2008. Print.

Farey, John. *A Treatise on the Steam Engine Historical, Practical and Descriptive*. London: Longman, Rees, Orme, Brown, and Green, 1827. Print.

Ferguson, Eugene. "The Steam Engine before 1830." *Technology in Western Civilization*. Ed. Melvin Kranzberg and Carroll W. Pursell. New York: Oxford U, 1967a. N. pag. Print.

Ferguson, Eugene. "Metallurgical and Machine-Tool Developments." *Technology in Western Civilization*. Ed. Melvin Kranzberg and Carroll W. Pursell. New York: Oxford U, 1967b. N. pag. Print.

Figuier, Louis. *Histoire Du Merveilleux Dans Les Temps Modernes*. Paris: L. Hachette Et Cie, 1860. Print.

"The Financial System: What Went Wrong." *Economist*. N.p., 19 Mar. 2008. Web. 15 May 2016.

Fisher, Matthew. "Darcy v. Allen." *Landmark Intellectual Property Cases and Their Legacy: IEEM International Intellectual Property Conferences*. Ed. Christopher Heath and Anselm Kamperman Sanders. Alphen Aan Den Rijn, The Netherlands: Kluwer Law International, 2011. 63-80. Print.

Fleming, Donald. "Latent Heat and the Invention of the Watt Engine." *Isis* 43.1 (1952): 3-5. Web.

Floud, Roderick, and Donald N. McCloskey, eds. *The Economic History of Britain since 1700. Vol. 1*. Cambridge: Cambridge UP, 1981. Print.

Fogel, Robert W., and Stanley L. Engerman. *Time on the Cross: The Economics of American Negro Slavery*. Boston: Little, Brown, 1974. Print.

Fohlen, Claude. *The Industrial Revolution in France 1700-1914*. London: Collins, 1970. Print.

Forbes, R. J. "Power to 1850." *A History of Technology*. Ed. Charles Singer. Vol. 4. New York: Oxford UP, 1958. 148-67. Print.

Gallon, Jean-Gaffin. *Machines Et Inventions Approuvées Par L'Academie Royale Des Sciences Depuis Son Établissement Jusqu'à Présent; Avec Leur Description*. Paris: Gabriel Martin, 1735. Print.

Gaskell, P. *The Manufacturing Population of England; Its Moral, Social, and Physical Conditions, and the Changes Which Have Arisen from the Use of Steam Machinery; with an Examination of Infant Labour*. New York: Arno, 1972. Print.

Geiger, Reed G. *The Anzin Coal Company, 1800-1833: Big Business in the Early Stages of the French Industrial Revolution*. Newark: U of Delaware, 1974. Print.

Gentle, Rupert, and Rachael Feild. *English Domestic Brass, 1680-1810, and the History of Its Origins*. New York: Dutton, 1975. Print.

Gies, Frances, and Joseph Gies. *Cathedral, Forge, and Waterwheel: Technology and Invention in the Middle Ages*. New York: HarperCollins, 1994. Print.

Gilbert, K. R. "Machine-Tools." *A History of Technology*. Ed. Charles Singer. Vol. 4. New York: Oxford UP, 1958. 417-57. Print.

Gilbert, K. R. *The Portsmouth Block-making Machinery; a Pioneering Enterprise in Mass Production*. London: H.M. Stationery Office, 1965. Print.

Gillispie, Charles Coulston. *Science and Polity in France: The End of the Old Regime*. Princeton, NJ: Princeton UP, 2004. Print.

Godley, Andrew. *Jewish Immigrant Entrepreneurship in New York and London, 1880-1914: Enterprise and Culture*. Houndmills, Basingstoke, Hampshire: Palgrave, 2001. Print.

Gould, Stephen Jay. *Bully for Brontosaurus: Reflections in Natural History*. New York: Norton, 1991. Print.

Granger. *Magdeburg Hemisphere, 1672*. 2012. *Fine Art America*. Web.

Greif, Avner. "Historical and Comparative Institutional Analysis." *The American Economic Review* 88.2, Papers and Proceedings of the Hundred and Tenth Annual Meeting of the American Economic Association (1998): 80-84. *JSTOR*. Web. 12 May 2016.

Greif, Avner. *Institutions and the Path to the Modern Economy: Lessons from Medieval Trade*. Cambridge: Cambridge UP, 2006. Print.

Gross, Bill. "The Single Biggest Reason Why Startups Succeed." TED2015. Vancouver, Canada. Mar. 2015. *TED.com*. Web. 15 May 2016.

Habakkuk, H. J. "English Population In The Eighteenth Century." *The Economic History Review* 6.2 (1953): 117-33. Web.

Hagen, E. E. "British Personality and the Industrial Revolution: The Historical Evidence." *Social Theory and Economic Change*. Ed. Tom Burns and S. B. Saul. London: Tavistock Publications, 1967. 35-66. Print.

Hahn, Roger. *The Anatomy of a Scientific Institution: The Paris Academy of Sciences, 1666-1803*. Berkeley, Los Angeles: U of California, 1971. Print.

Hall, Rupert A. "What Did the Industrial Revolution in Britain Owe to Science?" *Historical Perspectives: Studies in English Thought and Society, in Honour of J.H. Plumb*. Ed. J. H. Plumb and Neil McKendrick. London: Europa, 1974. N. pag. Print.

Hamilton, Henry. *The English Brass and Copper Industries: To 1800*. New York: Augustus M. Kelley, 1967. Print.

Harrington, J. C. *A Tryal of Glasse: The Story of Glassmaking at Jamestown*. Richmond, VA: Dietz, 1972. Print.

Harris, J. R. "The Employment Of Steam Power In The Eighteenth Century." *History* 52.175 (1967): 133-48. Web.

Harris, J. R. "Skills, Coal And British Industry In The Eighteenth Century." *History* 61.202 (1976): 167-82. Web.

Harris, J. R. *Essays in Industry and Technology in the Eighteenth Century: England and France*. Hampshire, Gt. Brit.: Variorum, 1992. Print.

Harris, J. R. *Industrial Espionage and Technology Transfer: Britain and France in the Eighteenth Century*. Aldershort, Hants, England: Ashgate Pub., 1998. Print.

Harris, Ron. "The Bubble Act: Its Passage and Its Effects on Business Organization." *The Journal of Economic History* 54.03 (1994): 610-27. Print.

Hatcher, John. *The History of the British Coal Industry*. Vol. 1 Before 1700. Oxford: Clarendon, 1993. Print.

Heilbron, J. L. "The Measure of Enlightenment." *The Quantifying Spirit in the 18th Century*. Ed. Tore Frängsmyr and Robin E. Rider. Berkeley: U of California, 1990. 207-43. Print.

Helfferich, Tryntje. *The Thirty Years War: A Documentary History*. Indianapolis: Hackett Pub., 2009. Print.

Henderson, W. O. *The Industrial Revolution on the Continent: Germany, France, Russia, 1800-1914*. London: F. Cass, 1961. Print.

Hendry, David F. "Econometrics-Alchemy or Science?" *Economica* 47.188 (1980): 387-406. Web.

Herndon, Thomas, Michael Ash, and Robert Pollin. "Does High Public Debt Consistently Stifle Economic Growth? A Critique of Reinhart and Rogoff." *Cambridge Journal of Economics* 38.2 (2013): 257-79. Web.

Hicks, John. *The Theory of Wages*. London: Macmillan, 1963. Print.

Hilaire-Pérez, Liliane. *L'invention Technique Au Siècle Des Lumières*. Paris: A. Michel, 2000. Print.

Hills, Richard Leslie. *Power in the Industrial Revolution*. Manchester: Manchester U.P., 1970. Print.

Hills, Richard Leslie. *Power from Steam: A History of the Stationary Steam Engine*. Cambridge: Cambridge UP, 1989. Print.

Hills, Richard Leslie. *James Watt*. Ashbourne: Landmark, 2002. Print.

Hobbes, Thomas. *Thomas Hobbes: Leviathan*. Bristol: Thoemmes Continuum, 2003. Print.

Hoffman, Philip T. "Institutions and Agriculture in Old Regime France." *Politics & Society* 16.2-3 (1988): 241-64. Web.

Hoffman, Philip T., Gilles Postel-Vinay, and Jean-Laurent Rosenthal. *Priceless Markets: The Political Economy of Credit in Paris, 1660-1870*. Chicago: U of Chicago, 2000. Print.

Hogben, Lancelot Thomas, and J. F. Horrabin. *Science for the Citizen; a Self-educator Based on the Social Background of Scientific Discovery*. New York: A.A. Knopf, 1938. Print.

Hollister-Short, Graham, ed. *History of Technology*. Vol. 20. London: Mansell, 1999. Print.

Horn, Jeff. "'A Beautiful Madness': Privilege, the Machine Question and Industrial Development in Normandy in 1789." *Past & Present* 217.1 (2012): 149-85. Web.

Hoselitz, Bert F. "Entrepreneurship and Capital Formation in France and Britain since 1700." *Capital Formation and Economic Growth; a Conference of the Universities-National Bureau Committee for Economic Research*. Ed. Universities National Bureau. Princeton: Princeton UP, 1955. 289-336. Print.

Humphries, J. ",English Apprenticeship: A Neglected Factor in the Industrial Revolution." *The Economic Future in Historical Perspective*. Ed. Paul A. David and Mark Thomas. Oxford: Oxford UP, 2003. 73-102. Print.

Hunter, Michael Cyril William. *Establishing the New Science: The Experience of the Early Royal Society*. Woodbridge, Suffolk: Boydell, 1989. Print.

Jacob, Margaret C. *Scientific Culture and the Making of the Industrial West*. New York: Oxford UP, 1997. Print.

Jacob, Margaret C. *Strangers Nowhere in the World: The Rise of Cosmopolitanism in Early Modern Europe*. Philadelphia: U of Pennsylvania, 2006. Print.

Jacob, Margaret C. *The First Knowledge Economy: Human Capital and the European Economy, 1750-1850*. Cambridge: Cambridge UP, 2014. Print.

Jacob, Margaret C., and Larry Stewart. *Practical Matter: Newton's Science in the Service of Industry and Empire, 1687-1851*. Cambridge, MA: Harvard UP, 2004. Print.

Jay, Peter. *The Wealth of Man*. New York: Public Affairs, 2000. Print.

Jervis-Smith, Frederick John. *Evangelista Torricelli. Written on the Occasion of the Tercentenary Commemoration of the Italian Philosopher, at Faenza, October 15 and 16, 1908*. Oxford: U, 1908. Print.

Jones, Peter. *Industrial Enlightenment: Science, Technology and Culture in Birmingham and the West Midlands, 1760-1820*. Manchester: Manchester UP, 2008. Print.

Kanefsky, John, and John Robey. "Steam Engines in 18th-Century Britain: A Quantitative Assessment." *Technology and Culture* 21.2 (1980): 161. Web.

Kemp, Tom. *Industrialization in the Non-Western World*. London: Longman, 1969. Print.

Kent, P. W., and Allan Chapman. *Robert Hooke and the English Renaissance*. Leominster, Herefordshire: Gracewing, 2005. Print.

Keyder, Caglar. "State and Industry in France, 1750-1914." *The American Economic Review* 75.2, Papers and Proceedings of the Ninety-Seventh Annual Meeting of the American Economic Association (1985): 308-14. *JSTOR*. Web. 15 May 2016.

Keyser, Barbara Whitney. "Between Science and Craft: The Case of Berthollet and Dyeing." *Annals of Science* 47.3 (1990): 213-60. Print.

Khan, B. Zorina. *The Democratization of Invention: Patents and Copyrights in American Economic Development, 1790-1920*. Cambridge: Cambridge UP, 2005. Print.

Khan, B. Zorina, and Kenneth L. Sokoloff. "“Schemes of Practical Utility”: Entrepreneurship and Innovation Among “Great Inventors” in the United States, 1790–1865." *The Journal of Economic History* 53.02 (1993): 289-307. Print.

Khan, B. Zorina, and Kenneth L. Sokoloff. "Institutions and Technological Innovation During the Early Economic Growth: Evidence from the Great Inventors of the United States, 1790-1930." *American Economic Review* 94.2 (2004): 395-401. Print.

Kindleberger, Charles Poor. *Economic Growth in France and Britain, 1851-1950*. Cambridge, MA: Harvard UP, 1964. Print.

King, Mike. *Quakernomics: An Ethical Capitalism*. London: Anthem, 2014. Print.

King, Peter. "The Choice of Fuel in the Eighteenth-century Iron Industry: The Coalbrookdale Accounts Reconsidered." *The Economic History Review* 64.1 (2011): 132-56. Web.

King, Peter W. "Sir Clement Clerke and the Adoption of Coal in Metallurgy." *Transactions of the Newcomen Society* 73.1 (2001): 33-52. Web.

Kitsikopoulos, Harry. *Innovation and Technological Diffusion: An Economic History of Early Steam Engines*. London: Routledge, 2016. Print.

Kranzberg, Melvin. "Prerequisites for Industrialisation." *Technology in Western Civilisation*. Ed. Melvin Kranzberg and Carroll W. Pursell. Vol. 1. New York: Oxford U.P, 1967. N. pag. Print.

Lamb, George J. "Coal Mining in France, 1873 to 1895." *The Journal of Economic History* 37.01 (1977): 255-57. Print.

Landes, David S. *The Unbound Prometheus: Technological Change and Industrial Development in Western Europe from 1750 to the Present*. London: Cambridge U.P., 1969. Print.

Landes, David S. *The Wealth and Poverty of Nations: Why Some Are so Rich and Some so Poor*. New York: W.W. Norton, 1998. Print.

Lane, Nick. *The Vital Question: Energy, Evolution, and the Origins of Complex Life*. New York: W. W. Norton, 2015. Print.

Lauder, James Eckford. *James Watt and the Steam Engine: The Dawn of the Nineteenth Century*. 1855. Scottish National Gallery, n.p.

Le Clerc. *The Academy and Its Protectors*. 1671. Engraving. Bibliothèque Nationale, Paris.

Leamer, Edward E. "Let's Take the Con Out of Econometrics." *The American Economic Review* 73.1 (1983): 31-43. *JSTOR*. Web. 15 May 2016.

Leifchild, John R. *Cornwall: Its Mines and Miners*. London: Cass, 1968. Print.

Lindert, Peter H., and Jeffrey G. Williamson. "Revising England's Social Tables 1688–1812." *Explorations in Economic History* 19.4 (1982): 385-408. Print.

Lord, John. *Capital and Steam-power: 1750-1800*. London: Cass, 1966. Print.

Lucas, Robert E. "On the Mechanics of Economic Development." *Journal of Monetary Economics* 22.1 (1988): 3-42. Web.

Lyons, Henry. *The Royal Society 1660-1940*. Cambridge: Cambridge U.P, 1944. Print.

MacLeod, Christine. *Inventing the Industrial Revolution: The English Patent System, 1660-1800*. Cambridge: Cambridge UP, 1988. Print.

MacLeod, Christine. *Heroes of Invention: Technology, Liberalism and British Identity, 1750-1914*. Cambridge, UK: Cambridge UP, 2007. Print.

Macleod, Christine, and Alessandro Nuvolari. "The Pitfalls of Prosopography: Inventors in the "Dictionary of National Biography"" *Technology and Culture* 47.4 (2006): 757-76. *JSTOR*. Web. 16 May 2016.

Malthus, T. R. *An Essay on the Principle of Population: The First Edition (1798) with Introduction and Bibliography*. Comp. E. A. Wrigley and David Souden. London: W. Pickering, 1986. Print.

Marczewski, Jan. "Some Aspects of the Economic Growth of France, 1660-1958." *Economic Development and Cultural Change* 9.3 (1961): 369-86. Web.

Marx, Karl. *A Contribution to the Critique of Political Economy*. Chicago: C.H. Kerr, 1904. Print.

Mason, Stephen F. *A History of the Sciences*. New York: Collier, 1962. Print.

Mathias, Peter. *The Transformation of England: Essays in the Economic and Social History of England in the Eighteenth Century*. New York: Columbia UP, 1979. Print.

McCloskey, Deirdre N. *The Bourgeois Virtues: Ethics for an Age of Commerce*. Chicago: U of Chicago, 2006. Print.

McCloskey, Deirdre N. *Bourgeois Dignity: Why Economics Can't Explain the Modern World*. Chicago: U of Chicago, 2010. Print.

McCloy, Shelby Thomas. *French Inventions of the Eighteenth Century*. Lexington: U of Kentucky, 1952. Print.

Merton, Robert King. *The Sociology of Science: Theoretical and Empirical Investigations*. Chicago: U of Chicago, 1973. Print.

Mill, John Stuart. *Principles of Political Economy: With Some of Their Applications to Social Philosophy ; Books I - II*. Toronto: U of Toronto, 1996. Print.

Milward, Alan Steele., and Samuel Berrick. Saul. *The Economic Development of Continental Europe*. London: Allen and Unwin, 1973. Print.

Mitch, David. "The Role of Human Capital in the First Industrial Revolution." *The British Industrial Revolution: An Economic Perspective*. Ed. Joel Mokyr. Boulder: Westview, 1993. 267-307. Print.

Mokyr, Joel. "The Industrial Revolution and the New Economic History." *The Economics of the Industrial Revolution*. Ed. Joel Mokyr. Totowa, NJ: Rowman & Littlefield, 1985. 1-52. Print.

Mokyr, Joel. *The Lever of Riches: Technological Creativity and Economic Progress*. New York: Oxford UP, 1990. Print.

Mokyr, Joel, ed. *The British Industrial Revolution: An Economic Perspective*. Boulder: Westview, 1993. Print.

Mokyr, Joel. *The Gifts of Athena: Historical Origins of the Knowledge Economy*. Princeton: Princeton UP, 2002. Print.

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

Muirhead, James Patrick. *The Life of James Watt, with Selections from His Correspondence*. London: J. Murray, 1858. Print.

Musson, A. E. *Science, Technology, and Economic Growth in the Eighteenth Century*. London: Methuen, 1972. Print.

Musson, A. E., and Eric Robinson. *Science and Technology in the Industrial Revolution*. Toronto: U of Toronto, 1969. Print.

Nef, John U. *The Rise of the British Coal Industry*. London: Routledge, 1932. Print.

North, Douglass C. *Structure and Change in Economic History*. New York: Norton, 1981. Print.

North, Douglass C. *Institutions, Institutional Change, and Economic Performance*. Cambridge: Cambridge UP, 1990. Print.

North, Douglass C., and Robert Paul Thomas. *The Rise of the Western World; a New Economic History*. Cambridge: U, 1973. Print.

North, Douglass C., and Barry Weingast. "Constitutions and Commitment: The Evolution of Institutions Governing Public Choice in Seventeenth-Century England." *The Journal of Economic History* 49.4 (1989): 803-32. *JSTOR*. Web. 15 May 2016.

Oberle, Tim. *Process Techniques for Engineering High-performance Materials*. N.p.: CRC, 2013. Print.

O'Brien, Patrick, and Çağlar Keyder. *Economic Growth in Britain and France, 1780-1914: Two Paths to the Twentieth Century*. London: G. Allen & Unwin, 1978. Print.

O'Brien, Patrick. "The Political Economy of British Taxation, 1660-1815." *The Economic History Review* 41.1 (1988): 1-32. Print.

Oldroyd, David. *Estates, Enterprise and Investment at the Dawn of the Industrial Revolution: Estate Management and Accounting in the North-East of England, C.1700-1780*. Aldershot, England: Ashgate, 2007. Print.

Osinsky, Pavel, and Jari Eloranta. "Longitudinal Comparative Historical Analysis: Challenges and Possibilities." *Comparing Post-war Japanese and Finnish Economies and Societies: Longitudinal Perspectives*. Ed. Yasushi Tanaka. London: Routledge., 2014. 10-17. Print.

Pacey, Arnold. *The Maze of Ingenuity: Ideas and Idealism in the Development of Technology*. Cambridge, MA: MIT, 1992. Print.

Painting of a Colliery. 1790. Walker Art Gallery, Merseyside County Council.

Palmade, Guy P. *French Capitalism in the Nineteenth Century*. New York: Barnes & Noble, 1972. Print.

Papin, Denis. *A New Digester, or Engine for Softening Bones Containing the Description of Its Make and Use in These Particulars: Cookery, Voyages at Sea, Confectionary, Making of Drinks, Chymistry, and Drying: With an Account of the Price a Good Big Engine Will Cost and of the Profit It Will Afford*. London: H. Bonwicke, 1681. Print.

Parker, William N. *Europe, America, and the Wider World: Essays on the Economic History of Western Capitalism*. Cambridge: Cambridge UP, 1984. Print.

Payen, Jacques. *Capital Et Machine À Vapeur Au XVIIIe Siècle; Les Frères Périer Et L'introduction En France De La Machine À Vapeur De Watt*. Paris: Mouton, 1969. Print.

Perkin, Harold James. *The Origins of Modern English Society 1780-1880*. London: Routledge & K. Paul, 1969. Print.

Persson, Karl Gunnar. *An Economic History of Europe: Knowledge, Institutions and Growth, 600 to the Present*. Cambridge, UK: Cambridge UP, 2010. Print.

Poirier, Jean-Pierre, and R. Balinski. *Lavoisier, Chemist, Biologist, Economist*. Philadelphia, PA: U of Pennsylvania, 1996. Print.

Pollard, Sidney. "Industrialization and the European Economy." *The Economics of the Industrial Revolution*. Ed. Joel Mokyr. Totowa, NJ: Rowman & Allanheld, 1985. 165-76. Print.

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

Porter, Roy. *The Creation of the Modern World: The Untold Story of the British Enlightenment*. New York: W.W. Norton, 2000. Print.

Porter, Roy. *The Enlightenment*. Houndmills, Basingstoke, Hampshire: Palgrave, 2001. Print.

Price, Roger. *An Economic History of Modern France, 1730-1914*. London: Macmillan, 1981. Print.

Ragin, Charles C. *The Comparative Method: Moving beyond Qualitative and Quantitative Strategies*. Berkeley: U of California, 1987. Print.

Reinhart, Carmen, and Kenneth Rogoff. "Reinhart-Rogoff Response to Critique." *Wall Street Journal*. N.p., 16 Apr. 2013. Web. 15 May 2016.

Reinhart, Carmen M., and Kenneth S. Rogoff. "Growth in a Time of Debt." *The American Economic Review* 100.2 (2010): 573-78. *JSTOR*. Web. 15 May 2016.

Reinhart, Carmen M., and Kenneth S. Rogoff. "Reinhart and Rogoff: Responding to Our Critics." *New York Times* 25 Apr. 2013, Op Ed sec.: n. pag. Print.

Reis, Jaime. "Economic Growth, Human Capital Formation and Consumption in Western Europe Before 1800." *Living Standards in the Past: New Perspectives on Well-being in Asia and Europe*. Ed. Robert C. Allen, Tommy Bengtsson, and Martin Dribe. Oxford: Oxford U, 2005. 195-226. Print.

"René Antoine Ferchault De Réaumur." *Wikipedia*. Wikimedia Foundation, 02 May 2016. Web. 15 May 2016.

Reynolds, Terry S. *Stronger than a Hundred Men: A History of the Vertical Water Wheel*. Baltimore: Johns Hopkins UP, 1983. Print.

Robinson, Eric. "Matthew Boulton and the Art of Parliamentary Lobbying." *The Historical Journal* 7.02 (1964): 209-29. Print.

Robison, John. "Steam Engine." *Encyclopedia Britannica*. 3rd ed. Edinburgh: A. Bell and C. Macfarquhar, 1797. Print.

Roehl, Richard. "French Industrialization: A Reconsideration." *Explorations in Economic History* 13.3 (1976): 233-81. Print.

Rolt, L. T. C., and J. S. Allen. *The Steam Engine of Thomas Newcomen*. Hartington, Eng.: Moorland, 1977. Print.

Romer, David. *Advanced Macroeconomics*. New York, NY: McGraw-Hill/Irwin, 2012. Print.

Romer, Paul M. "Endogenous Technological Change." *Journal of Political Economy* 98.5, Part 2 (1990): n. pag. Web.

Romer, Paul M. "Increasing Returns and Long-Run Growth." *Journal of Political Economy* 94.5 (1986): 1002-037. Print.

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

Rosenberg, Nathan, and L. E. Birdzell. *How the West Grew Rich: The Economic Transformation of the Industrial World*. New York: Basic, 1986. Print.

Rosenberg, Nathan. "The Direction of Technological Change: Inducement Mechanisms and Focusing Devices." *Economic Development and Cultural Change* 18.1, Part 1 (1969): 1-24. Web.

Rosenberg, Nathan. *Perspectives on Technology*. Cambridge: Cambridge UP, 1976. Print.

Rosenthal, Jean-Laurent. "The Development of Irrigation in Provence, 1700-1860: The French Revolution and Economic Growth." *The Journal of Economic History* 50.03 (1990): 615-38. Print.

Rossman, Joseph. *The Psychology of the Inventor; a Study of the Patentee*. Washington, D.C.: Inventors, 1931. Print.

Russell, Ben. *James Watt: Making the World Anew*. London: Reaktion, 2014. Print.

Samuelsson, Kurt. "Religion and Economic Action'" *Protestantism, Capitalism, and Social Science: The Weber Thesis Controversy*. Ed. Robert W. Green. Lexington, MA: Heath, 1973. 137-49. Print.

Savery, Thomas. *The Miner's Friend; Or, an Engine to Raise Water by Fire ..* London: S. Crouch, 1702. Print.

Say, Jean Baptiste. *A Treatise on Political Economy*. Trans. Charles Robert. Prinsep. Vol. 1. London: Longman, Hurst, Rees, Orme & Brown, 1821. Print.

Scherer, F. M. *Innovation and Growth: Schumpeterian Perspectives*. Cambridge, MA: MIT, 1986. Print.

Scherer, F. M. "Invention and Innovation in the Watt-Boulton Steam-Engine Venture." *Technology and Culture* 6.2 (1965): 165-87. *JSTOR*. Web. 13 May 2016.

Schultz, Theodore W. "Investment in Human Capital." *The American Economic Review* 51.1 (1961): 1-17. *JSTOR*. Web. 02 May 2016.

Schumpeter, Joseph A. *The Theory of Economic Development; an Inquiry into Profits, Capital, Credit, Interest, and the Business Cycle*. Trans. Redvers Opie. Cambridge, MA: Harvard UP, 1934. Print.

Scoville, Warren Candler. *The Persecution of Huguenots and French Economic Development, 1680-1720*. Berkeley: U of California, 1960. Print.

Seccombe, Thomas. "Henry Somerset." *Dictionary of National Biography*. Ed. Sidney Lee, George Smith, and Leslie Stephen. London: Smith, Elder &, 1897. 242-45. Print.

Sée, Henri. *Economic and Social Conditions in France during the Eighteenth Century*. New York: Cooper Square, 1968. Print.

Shapin, Steven, and Simon Schaffer. *Leviathan and the Air-pump: Hobbes, Boyle, and the Experimental Life*. Princeton, NJ: Princeton UP, 2011. Print.

Skempton, A. W., ed. *John Smeaton*. London: Thomas Telford, 1981. Print.

Smeaton, John. *An Experimental Enquiry concerning the Natural Powers of Water and Wind to Turn Mills*. London: n.p., 1760. Print.

Smiles, Samuel. *Lives of the Engineers: The Steam Engine: Boulton and Watt*. London: J. Murray, 1874. Print.

Smith, Alan. "'Engines Moved by Fire and Water'." *Transactions of the Newcomen Society* 66.1 (1994): 1-25. Web.

Smith, Alan. "A New Way of Raising Water by Fire: Denis Papin's Treatise of 1707 and Its Reception by Contemporaries." *History of Technology*. Ed. Graham Hollister-Short. Vol. 20. London: Mansell, 1999. 139-82. Print.

Smith, Michael Stephen. *The Emergence of Modern Business Enterprise in France, 1800-1930*. Cambridge, MA: Harvard UP, 2006. Print.

Solow, Robert M. *Growth Theory: An Exposition*. New York: Oxford UP, 2000. Print.

Solow, Robert M. "Technical Change and the Aggregate Production Function." *The Review of Economics and Statistics* 39.3 (1957): 312-20. *JSTOR*. Web. 15 May 2016.

Stasavage, David. *Public Debt and the Birth of the Democratic State: France and Great Britain, 1688-1789*. Cambridge: Cambridge UP, 2003. Print.

Stirk, Nigel. "Intellectual Property and the Role of Manufacturers: Definitions from the Late Eighteenth Century." *Journal of Historical Geography* 27.4 (2001): 475-92. Print.

Stuart, Robert. *Stuart's Descriptive History of the Steam Engine*. London: J. Chidley, 1831. Print.

Sullivan, Richard J. "England's "Age of Invention": The Acceleration of Patents and Patentable Invention during the Industrial Revolution." *Explorations in Economic History* 26.4 (1989): 424-52. Web.

Szostak, Rick. *The Role of Transportation in the Industrial Revolution: A Comparison of England and France*. Montreal: McGill-Queen's UP, 1991. Print.

Terry, Sheila. *Hero of Alexandria*. N.d. Science Photo Library. *Fine Art America*. Web.

Thompson, Benjamin. *Inventions, Improvements, and Practice of Benjamin Thompson, in the Combined Character of Colliery Engineer, and General Manager with Some Interesting Particulars Relative to Watt's Steam Engine, and a Short Treatise on the Coal Trade Regulation*. Newcastle: M. and M.W. Lambert, 1847. Print.

Thurston, Robert Henry. *A History of the Growth of the Steam-engine*. N.p.: D. Appleton, 1878. Print.

Tobey, Alton. *A Newcomen Engine, Ca. 1700*. 1961. Paintings for "Man and Power", n.p.

Toynbee, Arnold. *Lectures on the Industrial Revolution of the 18th Century in England*. New York, NY: Humboldt, 1884. Print.

Trinder, Barrie Stuart. *The Darbys of Coalbrookdale*. Chichester: Phillimore, 1974. Print.

Tufte, Edward R. *The Cognitive Style of PowerPoint: Pitching out Corrupts within*. Cheshire, CT: Graphics, 2003. Print.

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

Usher, Abbott Payson. *A History of Mechanical Inventions*. Cambridge: Harvard UP, 1954. Print.

Vayssière, Pierre. "Un Pionnier De La Révolution Industrielle En Languedoc Au XVIIIe Siècle : John Holker." *Annales Du Midi : Revue Archéologique, Historique Et Philologique De La France Méridionale Anami* 79.83 (1967): 269-86. Web.

Velde, François R., and David R. Weir. "The Financial Market and Government Debt Policy in France, 1746-1793." *The Journal of Economic History* 52.1 (1992): 1-39. *JSTOR*. Web. 16 May 2016.

Voigtländer, Nico, and Hans-Joachim Voth. "Why England? Demographic Factors, Structural Change and Physical Capital Accumulation during the Industrial Revolution." *Journal of Economic Growth* 11.4 (2006): 319-61. Web.

Von Tunzelmann, N. G. *Steam Power and British Industrialization to 1860*. Oxford: Clarendon, 1978. Print.

Voth, Hans-Joachim. "Living Standards During the Industrial Revolution: An Economist's Guide." *American Economic Review* 93.2 (2003): 221-26. Web.

Wadsworth, Alfred P.., and Julia De Lacy. Mann. *The Cotton Trade and Industrial Lancashire 1600-1780*. Manchester: Manchester UP, 1931. Print.

Wallace, Anthony F. C. *The Social Context of Innovation: Bureaucrats, Families, and Heroes in the Early Industrial Revolution, as Foreseen in Bacon's New Atlantis*. Princeton, NJ: Princeton UP, 1982. Print.

Watt, James, and Joseph Black. *Partners in Science; Letters of James Watt and Joseph Black*. Comp. Eric Robinson and Douglas McKie. London: Constable, 1969. Print.

Weber, M. *Protestant Ethic and the Spirit of Capitalism*. London: Allen & Unwin, 1962. Print.

Weightman, Gavin. *The Industrial Revolutionaries: The Creation of the Modern World, 1776-1914*. London: Atlantic, 2007. Print.

Weightman, Gavin. *Eureka: How Invention Happens*. N.p.: Yale UP, 2015. Print.

Weir, David R. "Tontines, Public Finance, and Revolution in France and England, 1688-1789." *The Journal of Economic History* 49.1 (1989): 95-124. *JSTOR*. Web. 16 May 2016.

"What Was the Great Divergence?" *www.economist.com*. Ed. C.W. The Economist, 2 Sept. 2013. Web. 12 Feb. 2016.

Winston, Robert M. L. *Bad Ideas?: An Arresting History of Our Inventions*. London: Bantam, 2010. Print.

Wolfe, John J. *Brandy, Balloons & Lamps: Ami Argand, 1750-1803*. Carbondale: Southern Illinois UP, 1999. Print.

Woods, Robert. "Cugnot's Fardier." *Engineering and Technology History Wiki*. American Society of Mechanical Engineers, July 2012. Web. 2 May 2016.

Wrangham, Richard W. *Catching Fire: How Cooking Made Us Human*. New York: Basic, 2009. Print.

Wright, Joseph. *An Experiment on a Bird in the Air Pump*. 1768. Oil on canvas. National Gallery, London.

Wright, Peter D. *Life on the Tyne: Water Trades on the Lower River Tyne in the Seventeenth and Eighteenth Centuries, a Reappraisal*. London: Routledge, 2016. Print.

Ziegler, J. Nicholas. *Governing Ideas: Strategies for Innovation in France and Germany*. Ithaca: Cornell UP, 1997. Print.