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Scientific Background to the Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel 2025

The Committee for the Prize in Economic Sciences in Memory of Alfred Nobel

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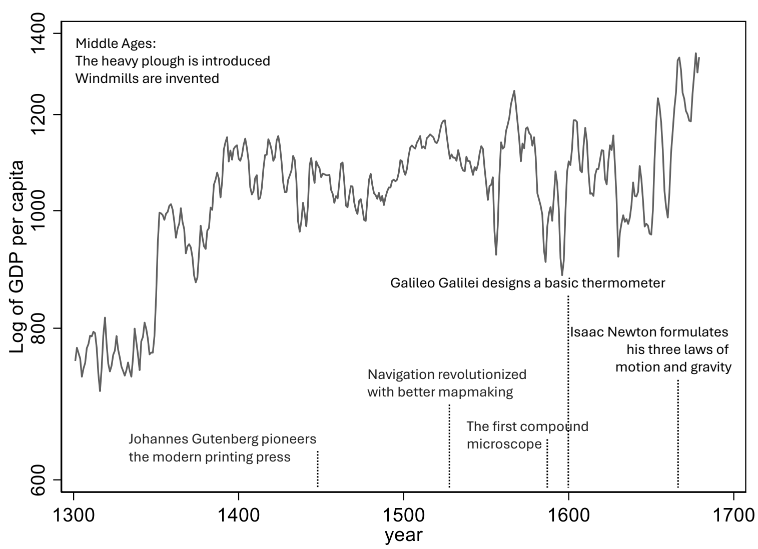
Sustained economic growth through technological progress

1 Introduction

On a daily basis, we are reminded of how fast technology progresses and how it changes the world around us. New discoveries and new innovations affect our lives directly and they also fundamentally affect the economy. Technological change is of course not a new phenomenon. Progress and innovations have occurred since ancient times. What is relatively recent, however, viewed against the entire history of humankind, is the type of innovation-driven economic growth enjoyed by the advanced countries of the world during the last two centuries, and how such high growth rates are sustained.

Figure 1 shows the striking lack of persistent economic growth for a longer pre-industrial period, despite some major scientific and technical breakthroughs. The picture shows GDP per capita in England, where historical national accounts have been constructed going back to the 13th century (Broadberry et al., 2015), and is broadly representative of human history across the world up until 1700.

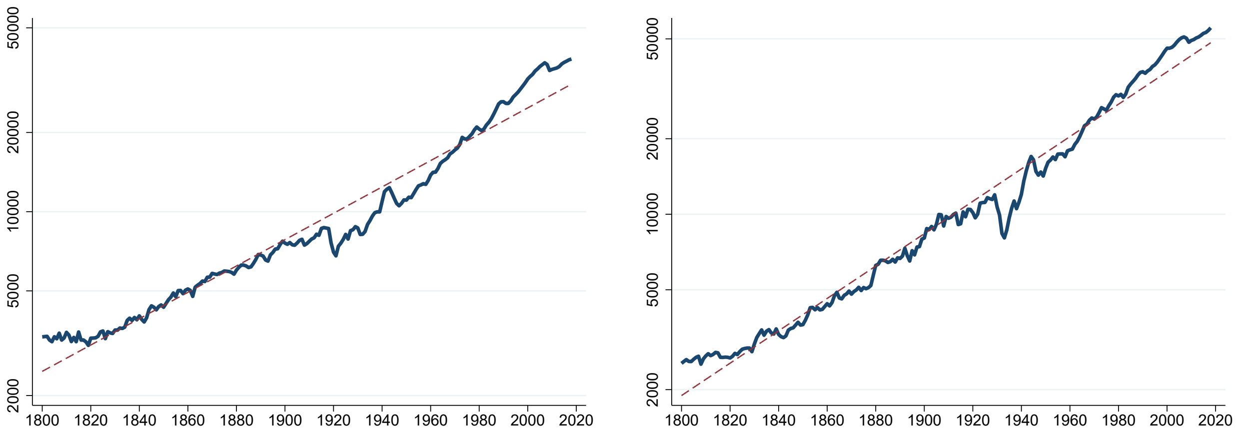
Figure 1: GDP per capita in England 1300–1680, paired with selected innovations and breakthroughs



GDP per capita in Geary-Khamis 1990 dollars. The y-axis is logarithmic. *Data sources:* Broadberry et al. (2015).

In contrast to Figure 1, Figure 2 shows economic growth since 1800 of two countries at the world's technological frontier: the United Kingdom (panel (a) on the left) and the United States (panel (b) on the right). Although these countries have experienced significant turbulence over this time period, and swings or dips are visible in this graph, the most striking aspect of the figure is the long period of remark-

Figure 2: Real GDP per capita, 1800–2018



(a) United Kingdom

(b) United States

GDP per capita in USD in 2011 prices. The y-axes are logarithmic, i.e., a straight line can be interpreted as a constant growth rate. *Data source:* Maddison Project Database 2023 with underlying sources for the United Kingdom: Broadberry et al. (2015) and for the U.S.: Sutch (2006) and de la Escosura (2009).

ably sustained economic growth.[1] How could economic growth become a sustained phenomenon? And what keeps us on the current path? These are first-order questions for the economies of the world. This year's laureates have addressed these questions in highly complementary research efforts from different perspectives and with different methods.

Joel Mokyr, an economic historian, studied how growth became sustained as a result of a set of key prerequisites that were not jointly present prior to the Industrial Revolution, but have been since then. Of central importance is how science interacts with technology, i.e., economic production in practice and that society welcomes technological change. One of his main study objects, quite naturally, was the Industrial Revolution, since it defined the transition between the two regimes in Figures 1 and 2. **Philippe Aghion** and **Peter Howitt** instead were inspired by the sustained economic growth of modern times and how disruptive this process is underneath the aggregate. They developed a theory of growth through "creative destruction", describing the process of innovation and "business stealing" and how the long-run growth rate of an economy is determined as a result. The theory contains fundamental building blocks of how new technology surpasses old, where some firms win at the expense of other firms, in an economy characterized by constant churning.

The starting point of this year's laureates contributions is the view that innovation and technological change are the key drivers of sustained economic growth. This point was forcefully made by Robert Solow (1986 economics laureate), whose growth accounting method (Solow, 1957) suggests that growth is not primarily driven by physical or human capital accumulation. The question of what drives technological change itself was not formally addressed until the early 1990s, when Paul Romer (2018 economics laure-

[1] A similar pattern of sustained economic growth can be seen since 1800 in other advanced economies (see Appendix Figure A1).

ate) developed theories around knowledge accumulation and emphasized key attributes like the non-rival nature of ideas. These studies, however, did not address how economic growth could emerge in the first place as a sustained phenomenon, nor did they examine or empirically evaluate the exact mechanisms propelling growth further and further. Even taking for granted that innovations and technological change are the key driver of economic growth, innovations predate the period of sustained economic growth by millennia. This year's laureates both explain how innovations feed into sustained economic growth, and how a regime emerged in which new products and processes are continuously introduced in the marketplace despite the conflicting interests they create.

Mokyr's novel answer centers around how innovation accelerates when scientific breakthroughs and practical knowledge reinforce each other. In particular, his studies link a number of key observations. First, philosophical and theoretical advancements had been recorded dating back thousands of years. Second, the development of applied technology—new tools, products, and methods of production that are central ingredients into how production occurs—had been pushed forward for ages. Third, each of these phenomena had always occurred in relatively short bursts and, throughout time, ground to a halt. Taken together, this produced a pattern of economic growth that in most of human history resembled long periods of stagnation or very slow growth, punctuated by sudden outbursts of short-lived economic dynamism. All of this changed with the Industrial Revolution, when the world saw sustained growth rates for the first time in history. In a string of focused, but crucially related, contributions, Mokyr (1990a, 2002, 2009) arrived at a synthesis that puts the interplay between science and applied technology at the heart of the articulation. The Enlightenment, in particular, was a major burst to science, but it did not mechanically generate applications that led to economic growth; for that, the practitioners were key. At the same time, Mokyr also documents how new innovations challenged old ways and met resistance from established interest groups wanting to thwart technological change. Therefore, intellectual tolerance for new ways of thinking and openness to ideas was crucial for removing major roadblocks to technological progress. Practitioners, ready to engage with science, along with a societal climate embracing change, were, according to Mokyr, key reasons why the Industrial Revolution started in Britain. Mokyr's narrative is constructed from a wide variety of historical sources from all of human history and both qualitative and quantitative work. The narrative has also been successfully tested with econometric studies by Mokyr himself as well as others.

Rather than looking into the distant past, Aghion and Howitt were motivated by observing modern-day sustained, innovation-led growth in advanced economies. Aghion and Howitt set out to understand, via theoretical formalization, how entrepreneurs innovate: how they create new ideas and introduce better products and processes in the marketplace, and how their actions are shaped by the regulatory environment. In other words, being guided by how innovations come about in practice in today's society, Aghion and Howitt put entrepreneurs and their decisions at center stage and analyzed the process of creative destruction. The idea is that an innovation leads to business stealing: the innovation is carried out in one firm, or by one individual, but partially destroys the rents of others. They constructed a mathematical framework designed to study how individual decisions and conflicting interests at the microeconomic firm level can lead to steady output growth at the aggregate level. The theory is empirically persuasive—it matches a range of relevant microeconomic and macroeconomic facts—and generated an avalanche of follow-up studies linking competition and firm dynamics to growth. The basic model proposed by Aghion and Howitt (1992), and the literature that followed, described innovations not as complementary to pre-existing activities, as in Romer's work, but as another polar case whereby new goods are perfect substitutes with old ones, and in fact simply better than existing goods. This perspective introduces the elements of creative destruction and conflicting interests. Aghion and Howitt's approach fundamentally relies on the heterogeneity and competing relations among firms, allowing us to test the theories of aggregate growth, and quantify their mechanisms, by looking at microeconomic, firm-level data. It also allows us to evaluate counter-factual policy experiments explicitly, e.g., changes in patent protection, competition policies or R&D subsidies. Their model, with its countless extensions, has become the workhorse model for analyzing positive and normative questions regarding innovation-led growth.

Mokyr's broad perspective and Aghion and Howitt's analytical precision provide us with tools that are crucial in today's world. Sustained technological development has allowed human conditions to steadily improve for more than 200 years. Two centuries, however, is just a small fraction of human history and the continuation of this trend is not to be taken for granted. Impediments to the open exchange of ideas and fading support for science could pose future threats to economic growth. Another challenge is how to regulate dominant tech or pharmaceutical companies without harming the technological progress they create. At the same time, there are also opportunities: new technologies such as artificial intelligence could grease the positive feedback loop between science and applied technology and may—in the right regulatory and societal environment—even lead to faster progress. Together, the contributions of this year's laureates have provided us with tools and offer important insights into how to address threats to progress and make the best out of future opportunities.

The document proceeds as follows: the next section, Section 2, describes the findings by Mokyr in more detail. Section 3 then continues with a discussion of the contribution by Aghion and Howitt. Section 4 concludes.

2 The takeoff into a long era of growth

Part of this year's Prize in Economic Sciences is awarded to Mokyr for having provided an explanation for how industrial takeoffs can transform into sustained and self-propelling economic growth. By contrasting the sporadic searches and haphazardness that characterized the invention process throughout most of human history with the scientific research program that took hold of Europe after the Enlightenment, Mokyr (1990a, 2002, 2009) explains why economic growth did not peter out after the first decades of the Industrial Revolution. The Enlightenment, a pan-European movement, paved the way for a fruitful dialogue between theoretical and practical knowledge and created the virtuous cycles of knowledge accumulation that allowed Europe (or more specifically, Britain) to embark on an innovation process powerful enough to generate sustained growth for the first time in history. It was not until the British Industrial Revolution that the modern process of creative destruction emerged. This was when cumulative knowledge had become powerful enough to create new disruptive technologies, which were allowed to diffuse widely in society, despite destroying existing rents. As the “mother of all creative destruction” (Mokyr, 2020, p. 714), the Industrial Revolution provides a fundamental example of the forces needed to maintain a takeoff into sustained growth: a joint evolution of science and technology, mechanical competence and a wider acceptance of the forces of creative destruction.

Below, we begin by motivating the ideas about takeoff and sustained economic growth with historical data. The document then remarks on the point of departure in the literature when Mokyr’s work emerged. Thereafter, the contribution and the empirical evidence and empirical follow-up studies are described, and finally the impact of Mokyr’s work is discussed.

2.1 Motivating evidence

By studying technological creativity in various historical societies, Mokyr (1990a) noted that some societies were highly creative, while others were much less so, without this having much relationship to the process of economic growth. Yet history did experience periods of short-lived economic expansion. Figure 3 provides examples with recently constructed GDP per capita series from six European pre-industrial economies, summarized and discussed by Fouquet and Broadberry (2015). The figure shows that Italy (during the Renaissance of the 15th and 16th centuries), Sweden (during its Great Power Era in the 17th century), and Holland (during the Dutch Golden Age, commonly set between 1588 and 1672) all experienced pre-industrial growth periods that eventually fizzled out, failing to produce a takeoff.

Instead, the takeoff took place in Britain with the Industrial Revolution (dates commonly set between 1760 and 1830 by, e.g., Ashton (1948)). As shown in Figure 3, growth rates started to increase already in the late 17th century. However, what set Britain apart from the rest of the sample experiencing periods of positive growth was that these rates became sustained, building up to the first takeoff into modern economic growth.

Figure 4 places the takeoff in longer historical context. The figure clearly shows that any kind of pre-industrial growth displayed in Figure 3 is massively overshadowed by the type of growth that took off with the Industrial Revolution. After Britain, economic takeoffs into sustained growth have occurred in several countries. Today, growth rates averaging some 1–2% annually have become the norm in most industrial countries, as outlined in Appendix Figure A1. This new pattern of sustained economic growth has subsequently raised average GDP per capita in the world (see Figure 4) very significantly, which in practice means that the last centuries of human history have, for the first time, implied continuous, significant improvements in living standards. Given the contrast between “before” and “after,” a key question is what allowed the transition to occur. A related question is why did the transition not occur earlier, or later? And is there a risk of a reversal back to a stagnant era? It is into this complex set of questions that Mokyr’s research has given us crucial insights.

2.2 Points of departure

For most of the 20th century, historians and economic historians searched for clues by investigating a number of specificities of the British Industrial Revolution. A key hypothesis was that this important

Figure 3: GDP per capita in selected European Economies 1300–1800.

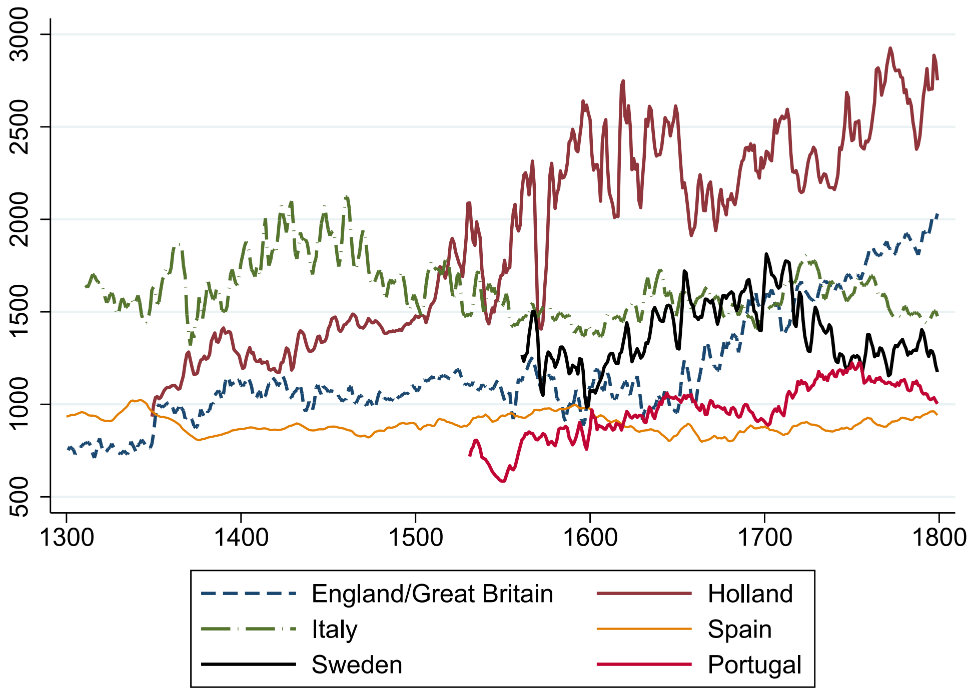


Figure notes. GDP per capita in Geary-Khamis 1990 dollars. All series in three-year average, except Spain (in 11-year average). The figure reproduces data published in Fouquet and Broadberry (2015). *Data sources:* England/Great Britain: Broadberry et al. (2015) (England from 1300 until 1700, Great Britain afterwards); Italy: Malanima (2011) (specifically central and northern Italian states from 1310); Holland: Van Zanden and Van Leeuwen (2012); Sweden: Schön and Krantz (2012); Spain: Alvarez-Nogal and De La Escosura (2013); Portugal: Palma and Reis (2019).

economic event could be explained by economic factors, such as relative prices, endowments, demand factors, investment, exports, savings, property rights, changes in labor supply, and fiscal and monetary institutions, that differed between Britain and other countries.[2] Among the many explanations, the role of science in the Industrial Revolution remained contentious. It was commonly argued that "science had little guidance to offer" (e.g., Hall (1974, p. 151)) and that only very few early inventions could be seen as directly traceable to new discoveries by scientists such as Galileo, Descartes, or Newton.[3] The standard view instead resorted to explaining the Industrial Revolution with factors already embedded in the European societies before the takeoff, with many scholars championing a vision of a gradually rising West, (e.g., North and Thomas (1973); Landes (1969, 1998)). For a long time, this view was also supported by the pioneering data collection in Maddison (2001), which gave tentative support to the idea that Western

[2]The literature on the causes of the Industrial Revolution is too broad to summarize here. The interested reader is referred to reference textbooks, such as chapter 24 in Blum and Colvin (2018), chapter 6 in Persson and Sharp (2025), chapter 8 in Koyama and Rubin (2022), or the editors introduction in Mokyr (2018a).

[3]See arguments by, e.g., Mathias (1972); McKendrick (1973); Landes (1969). A related point, as argued by Gillispie (1957), was that most scientific endeavors of the time were concerned with topics of limited technological use. Occasional counter-arguments about science's role in the Industrial Revolution are made by Musson and Robinson (1969) and Jacob (1997). Recently, the notion of a lack of scientific content in the Industrial Revolution has been promoted by Allen (2009).

Figure 4: GDP per capita 1252 to 2022.

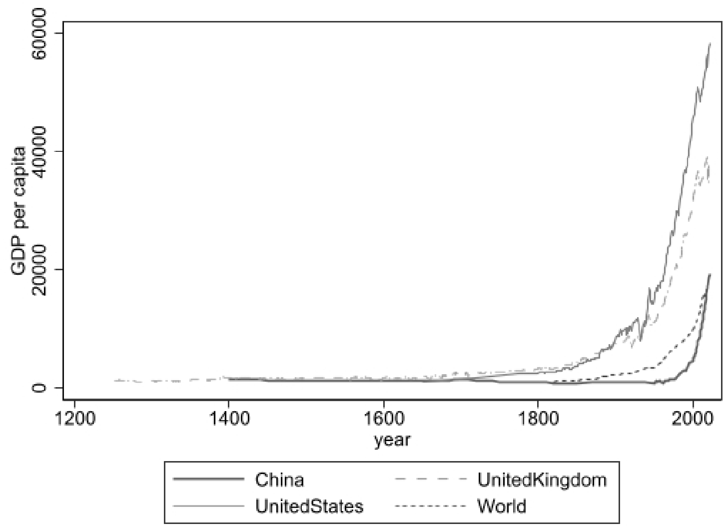


Figure notes. GDP per capita in USD in 2011 prices. *Data sources:* Maddison database (MPD 2023), with underlying sources for China: Broadberry et al. (2018); Xu et al. (2017); United States: McCusker (2006); Sutch (2006); de la Escosura (2009); United Kingdom: Broadberry et al. (2015).

Europe overtook China around the 16th century.[4]

Simultaneously a parallel literature in economic history focused on measurement of macroeconomic variables and producing long-time series (e.g., Deane and Cole (1962)). With the compilation and creation of new time series data, researchers noted the surprisingly low growth rates (by modern standards) during the allegedly revolutionary late 18th and early 19th century in Britain. A revisionist view of the Industrial Revolution emerged, viewing it as a gradual acceleration onto a steady but unspectacular growth path with rapid productivity advances confined to relatively few sectors (Harley, 1982; Crafts, 1985; Crafts and Harley, 1992).[5] The new quantitative evidence led some to argue that the Industrial Revolution had been "dethroned" almost entirely, leaving behind only a description of gradual structural change from agrarian to non-agrarian sectors (Berg and Hudson, 1992). Thus, there was barely anything left to explain.

2.3 Mokyr's contribution

Mokyr (1990a, 2002) adopted a different perspective. He reformulated the debate by centering it on the impact of technological change on growth. Tracing the inventions and innovations that have transformed society since ancient China, Greece and Rome, and then evaluating the role of each technology, he concluded that technology had historically failed to produce growth because little was known about how and why the techniques worked. It was "a world of engineering without mechanics, iron-making without

[4] This view was, however, challenged by the so-called California school that put China at par with Europe until about 1800 (Frank, 1998; Pomeranz, 2000). Lately, new comparative output estimates date the Great Divergence to around 1700; see the work by Broadberry et al. (2018, 2021).

[5] See Temin (1997) for a summary of the debate.

metallurgy, farming without soil science, mining without geology, water-power without hydraulics, dye-making without organic chemistry, and medical practice without microbiology and immunology" (Mokyr, 2005b, p. 1119).

To explain why technologies historically had failed to produce sustained growth, Mokyr (1990a,b) distinguished between major breakthroughs ("macro inventions") and incremental improvements ("micro inventions"). Macro inventions are radical technological discontinuities determined by some shift in people's knowledge or understanding or in a new combination of previously disparate ideas with potentially large effect on the marginal product of further improvements. Micro inventions, on the other hand, are incremental improvements to existing technologies explained by changes in economic supply and demand.[6] That is, micro inventions are closer to everyday economic life and provide a key link between technology and the economy.

While macro inventions were not new to history—e.g., think of the windmill, the printing press, or the weight-driven mechanical clock—they emerged sporadically and failed to generate a stream of cumulative micro inventions supplementing the new techniques. Likewise, the drift of cumulative micro inventions resulted in many incremental improvements that soon ran into diminishing returns in the absence of new, more abstract ideas that widened the horizon. When no one knew *why* things worked, even radical technological shifts failed to generate the applications that made them useful in production processes. In such a world, economic resources were not allocated towards improving technologies, as potential investors were just as likely to waste valuable resources on fruitless inventions that would never work, such as perpetual motion machines or artificially created gold (Mokyr, 2002, p. 31–32).

The lack of a positive feedback loop between macro and micro inventions meant that even radical technological shifts always failed to result in anything but another technological plateau. While periods with rapid technological change could sometimes almost resemble the very early stages of the Industrial Revolution, or a takeoff, new innovations never accumulated enough feedback to produce sustained growth, i.e., a burst of activity that lasted for more than a few decades. Thus, technological progress during the period before the Industrial Revolution was very different from what took place after. With this insight, Mokyr identified a number of key prerequisites for sustaining economic growth.

A joint evolution of science and technology. A first key prerequisite for sustained growth, according to Mokyr, is the joint evolution of science and technology. The main event that allowed the transition to begin was the Enlightenment. However, what ultimately drove the takeoff into sustained economic growth was an expansion of "useful knowledge" (a term first introduced by Kuznets (1965)), powerful enough to break out of the long-run stasis.

In *The Gifts of Athena*, Mokyr (2002) developed the theory of the knowledge economy as a driver of sustained growth, able to generate positive feedback loops between macro and micro inventions. To explain how the acquisition of knowledge transformed itself such that it could sustain the Industrial Revolution

[6]The term macro invention has become associated with the idea of a general purpose technology (GPT) (Bresnahan and Trajtenberg, 1995) since both terms refer to disruptive new technologies with transformative effects. But whereas a GPT must have wide applicafbility to other technologies, a macro invention need only bring about potentially great changes in general. Historical work points to the importance of complementarities between innovations in different types of technologies, where Dahmén (1950) discusses "development blocks" and Landes (1969), and Rosenberg (1976, 1982) mention complementarities too.

beyond its first decades, Mokyr (2002) argued that useful knowledge rests on two types of knowledge. The first relates to knowledge about natural phenomena and regularities of the physical world, and is referred to as "propositional knowledge". The second dictates how things work in practice and is referred to as "prescriptive knowledge". Propositional knowledge serves as the support for the techniques carried out when economic production takes place. Although broadly similar to the standard distinction between "science" and "applied technology", or "theory" and "empirical knowledge", the concepts differ. Propositional knowledge is not science in a modern sense, since it could contain theories and observations of importance to the way techniques were historically carried out, and yet today be regarded as incorrect. It was not until propositional knowledge started to contain more scientifically tested and tried components that the knowledge base came closer to the type of formal and generalized propositional knowledge that we today know as science.[7] While propositional knowledge feeds into prescriptive knowledge, prescriptive knowledge can generate feedback into propositional knowledge. The simplest feedback occurs when a technique is discovered by trial and error, and the fact that it works is registered as a known regularity of the world. Further testing and tweaking may add new and unexplained phenomena that further stimulate propositional knowledge. Similarly, changes in the execution of techniques may open up for new development of instruments and tools that further the feedback loop. The virtuous cycle is self-sustaining in the sense that the two types of knowledge are complementary and increase the marginal product of the other.

The Enlightenment revolutionized the way useful knowledge accumulated. To connect the scientific revolution of the 16th and 17th centuries to events taking place in the economy around a century later, Mokyr coined the term the "Industrial Enlightenment" (Mokyr, 2002, p. 35). This was a set of social changes that transformed the nature and size of propositional and prescriptive knowledge and their relationship. In Mokyr's conception of the Industrial Enlightenment these social changes came about to: (i) reduce access costs to prescriptive knowledge by surveying artisanal practises to determine which techniques were superior, (ii) understand why techniques worked by generalizing them and trying to connect them with the formal propositional knowledge of the time, and (iii) facilitate the interaction between those that controlled the propositional knowledge and those that implemented the techniques contained in prescriptive knowledge.

The Industrial Enlightenment created new standards of open science, scientific methods and a common vocabulary making useful knowledge more diffused and accessible. By facilitating interaction, generalized propositional knowledge spread beyond the "more arcane realms of mathematics and experimental philosophy to the more mundane worlds of the artisan, the mechanic and the farmer" (Mokyr, 2002, p. 36). Gradually, the connection between propositional and prescriptive knowledge became tighter. By 1800, useful knowledge started to have a real impact on the economy, sustaining technological change and growth. The feedback from technological success further inspired confidence in the propositional

[7] Propositional knowledge contains the observation, cataloging and classification of natural phenomena as well as the establishment of regularities and principles and natural laws governing these phenomena. Such a definition includes mathematics insofar as it is used to describe and analyze the regularities of nature. Propositional knowledge is thus *episteme*, the set of rules, assumptions, and discourses that determine what is considered legitimate knowledge and how it is produced and understood within a specific historical context, and prescriptive knowledge is *techne*, the arts, skills and crafts in the context of making or doing (Mokyr, 2002, p. 4–5).

knowledge underlying the techniques and advanced knowledge accumulation. Had it not been for the enlarged scientific knowledge base, technological progress would have slowed down, as in all previous historical instances of technical change. Instead, growth became sustained. Around 1870, science-based knowledge influenced virtually all branches of industrial production (Mokyr (2005b)).

Mechanical competence. New ideas need people that put them into economic use. Mechanical competence refers to the ability of agents to carry out the instructions derived from prescriptive knowledge. But the knowledge needed to execute a new technology is not the same as the knowledge needed to invent it. Technologically creative societies are those where highly educated people who think for themselves mingle with those who are skilled and produce goods and services for consumption. Crucial to economic growth were thus the skilled practitioners (sometimes referred to by Mokyr as "tinkerers," "tweakers" or "implementers") who possessed sufficient technical know-how to access new knowledge to read the blueprints, scale up the models, and install the equipment that put science into economic use, or in other words, people able to move easily between the world of abstraction and the practicalities of the lever, the cylinder and the spindle. The skills that mattered here were not just the average skills of the population (i.e., average literacy or schooling rates) but rather the skills and capabilities among the upper tail of those possessing human capital. Capable tinkerers ensured that new technologies kept being tweaked, tested, and improved, and that useful knowledge was put into economic applications.

A society open to change. The Enlightenment not only helped enlarge the scope of propositional knowledge and its connections to practical use, but it also governed the societal changes needed to release the disruptive forces of creative destruction into society. Pioneering a literature on the political economy of technological change, Mokyr (1990a, 1992) explained the frailty of the process of creative destruction. Mokyr documented that resistance to technology, a phenomenon largely ignored by historians, had been pervasive in history and often came from vested interests. These vested interests involved those whose assets (i.e., formal skills, tacit knowledge, reputation, specialized equipment, ownership of certain natural resources, or barriers to entry that secured monopoly positions, etc.) were somehow threatened by the new inventions. Vested interests could also be identified among those intellectuals who were opposed to new technology on principle (the latter being the main concern of Schumpeter (1942)). With the Enlightenment, however, a cultural shift in human beliefs and attitudes towards nature took place.[8] A new willingness to harness nature to human needs helped overcome the barriers to technological change by creating a "culture of growth" that formed the basis for social and institutional change.[9] Specifically, the Enlightenment paved the way for a new institutions that were flexible enough to encourage competition between interest groups and allow the winners to compensate the losers, for example by functioning par-

[8] This aspect is further elaborated in *A Culture of Growth*, where Mokyr (2016) digs deeper into the question why the Enlightenment took place in Europe. Stressing a pluralist society with a functioning market for ideas in combination with cultural changes taking place 1500–1700, the book offers the prelude to the Enlightenment and the subsequent Industrial Revolution. A parallel cultural explanation to the Industrial Revolution can be found by McCloskey (2016), who points towards ideas of "bourgeois dignity and equality" that gave a reason for ordinary people to innovate.

[9] The idea that cultural beliefs are the scaffolds on which institutions are built can be traced back to Greif (1994) and North (2004), but while these authors are primarily interested in the kind of beliefs that people hold about one another, Mokyr (2016) stresses the beliefs people hold about their physical milieu.

liaments where representatives from different interest groups could meet and negotiate their claims.[10] With these societal changes in place, the forces of creative destruction could be released into society for the first time.

2.4 Tests and evidence

Mokyr bolstered his theoretical proposition by providing three types of empirical evidence: macro-level comparisons, an analytical narrative through historical case studies, and quantitative evidence. Below, we illustrate each of these in turn.

2.4.1 Macro-level comparisons

With large macro-comparisons from different historical periods and parts of the globe, Mokyr demonstrates that history has seen several periods of technological change that failed to translate into sustained economic growth. In every instance, one or several aspects of the key ingredients producing sustained growth—a joint evolution of science and technology, mechanical competence, and social acceptance of creative destruction—were lacking.

For example, the civilizations of ancient Greece and Rome were distinguished by advances in philosophy, geometry, architecture, and political science. Yet, these advancements failed to translate into practical products and techniques that could have been used for the betterment of human needs. As a result, technological progress in sectors impacting material living standards, such as agriculture, textiles, and the use of power and materials, were modest (Mokyr, 1990a, p. 20–29). Similarly, the Renaissance brought back the classical ideals and helped advance them in large numbers of new technical "how-to" books and manuals that diffused across society. Still, the distance between propositional and prescriptive knowledge remained large and the lack of local skilled labor and mechanics made it difficult to put theoretical ideas into practical use. New visions therefore often ended up being unrealized, just like Leonardo da Vinci's thousands of sketches for machinery that were mostly left unrealized in his lifetime (Mokyr, 1990a, p. 72–73).

In contrast, the relatively backward society in medieval Europe (500–1500 AD)—often referred to as the "dark Middle Ages"—saw several practical innovations that transformed productive capacity. The three-field crop rotation system, the heavy plow, windmills, and bigger and better water wheels all served to increase agricultural production and energy utilization, resulting in urbanization and population growth. The problem was a general lack of understanding of why the things worked, resulting in an invention process that was too sporadic and scattered to generate a powerful takeoff into sustained growth.

The most central macro-level comparison in Mokyr's work is that with China. Until the 14th century, China had a lead in technological development over Europe. Major Chinese innovations in plowing, blast furnaces, textiles, time measurement, maritime technology, paper production, and the production

[10] The role of institutions adds to the large literature on the importance of institutions for growth associated with, e.g., the 1993 economics Laureate Douglass North and the 2024 economics Laureates Daron Acemoglu, Simon Johnson, and James Robinson (e.g., North and Thomas (1973); North (2004); Acemoglu et al. (2001)). Acemoglu et al. (2005) and North and Weingast (1989) further stress the role of the British parliament in solving commitment problems and putting constraints on the executive.

of porcelain, lacquers, explosives and pharmaceuticals eventually found their way to Europe, either as imports or by reinvention (Mokyr, 1990a, p. 209–219). Yet, China failed to experience an Industrial Revolution.[11] Instead, innovation gradually slowed down. In some sectors, such as clockmaking and shipbuilding, even technological retrogression took place (Mokyr, 1990a, p. 220). China failed to develop a system of formal logic (Mokyr, 1990a, p. 229), and was not able to make the shift from the experience-based process of invention to more science-based methods (Lin, 1995). As the technological process was government-controlled and manipulated/managed by the Chinese court, China was kept on a technologically stagnant path due to lack of open science and competition. The best illustration of the reversal of technological creativity is the complete halt of geographical exploration after 1430 by a decision from the Chinese imperial court.[12]

2.4.2 Analytical narrative

In part, Mokyr built his new perspective on innovation-driven growth on a large number of case studies, where his focus on why the Industrial Revolution was first seen in Britain is a prime example. His studies of vested interests also rest on numerous narratives. We now briefly discuss each of these.

Britain's early advantage. While the Enlightenment movement was common to Western Europe, it was Britain that first created synergies that accelerated sustained technological innovation and growth. Drawing on a variety of sources, Mokyr (1990a, 2002) arrived at a synthesis consistent with both the timing and place of the Industrial Revolution, summarized and developed at length in Mokyr (2009).[13]

The argument was based on inductive reasoning obtained from of a multitude of different primary sources, such as biographies, letters, philosophers' writing, technical manuals, government reports, and secondary sources (historiographies). Importantly, Mokyr (2009) stressed that the Industrial Revolution must be understood as a broader shift, involving the entire society.[14] Outside the common tales of cotton textiles, wrought iron and steam power, technical improvements were seen across activities as varied as watchmaking, shipping, glassmaking, brewing, road transport, paper making, candlemaking, gas lighting, water power, and making ceramics and machine tools. Additionally, important breakthroughs encompassed discoveries as diverse as Newcomen's atmospheric engine, the process of making soda, chlorine bleaching, the calculation of the trajectory of a projectile, the determination of longitude at sea, and small-

[11] The failure of China to undergo an Industrial Revolution has been named the Needham puzzle, after sinologist Joseph Needham, who documented Chinese innovations in several volumes called *Science and Civilisation in China*, the first one published in 1954.

[12] Within Europe, the Netherlands constitutes a useful comparison, as it was in many ways the most advanced economy in Europe and at the cutting edge of technology before the Industrial Revolution. Mokyr (2000) documents that its leadership became short-lived due to negative feedback loops when the narrow bridge that had been built between those who made and built things and those who explored the regularities of nature became even narrower. Despite high human capital and market-friendly institutions, the Netherlands failed to transform its leadership into an Industrial Revolution. By the middle of the 18th century "it seems that something had gone amiss in the way the Dutch were processing useful knowledge" (Mokyr, 2000, p. 512).

[13] The analytical narrative developed by Mokyr (2009) was critically reviewed by Crafts (2011) in conjunction with the arguments put forward in the analytical narrative developed in the contemporary book by Allen (2009). Crafts concludes, by stating that the explanations may be seen as complementary rather than competing, but added that although the arguments in both books have precursors in the historiography, in the case of Mokyr (2009) these refer to the components of the argument rather than to the synthesis (Crafts, 2011, p. 156).

[14] In particular, Mokyr notes that the Industrial Revolution was not as "industrial" and much less pertaining to "textiles and cotton" than commonly asserted. For instance, chapters 10 and 11 in Mokyr (2009) describe the fundamental changes in the service sectors of the British economy, a process of transformation often overlooked in textbooks and monographs.

pox inoculation and vaccination. Yet, it was not the early takeoff that produced the most crucial change, but rather the events in the early decades of the 19th century. This was when the feedback loops between propositional and prescriptive knowledge had become powerful enough to put the economy onto a new path, with innovation and growth rates that could be sustained over the long run.[15]

It was thus the Enlightenment that brought the type of advances in propositional knowledge that proved crucial for accelerating the rate of technological progress. However, as France is often described as the epicenter of this intellectual movement, it is clear that the Enlightenment alone did not generate the advantage Britain had to take off. A key aspect of the argument by Mokyr (2009) is therefore that Britain had a comparative advantage in generating micro inventions from useful knowledge. That is, Britain possessed a comparably large and well-trained supply of skilled artisans and engineers.[16] National celebrities such as James Watt, who improved the Newcomen steam engine, and Richard Arkwright, who invented the water frame and the modern cotton mill, stand out here. There were, however, many more: The Darbys of Coalbrookdale supplied the cylinders of the Newcomen engines; Arthur Woolf, the engineer and inventor of the compound steam engine; Bryan Donkin, who famously improved mechanized papermaking; or Joseph Bramah and Henry Maudslay, often regarded as the fathers of the British machine tool industry (Mokyr, 2009, p. 108–109). Below these famous industrialists were a layer of mechanics, clockmakers, toymakers, wood makers, glass cutters and metal workers, who understood the interdependence of mechanical parts and could experiment with novel usage of materials and techniques. With skills such as the ability to understand notation and spatial graphic representation and a basic sense of "what worked", these mechanics possessed a major competence to carry out and adapt the instructions in the blueprints that allowed for a stream of micro inventions that perfected the novel techniques. Without this pool of mechanics, inventors like Arkwright and Watt would not have been able to turn their ideas into usable products.

Finally, Britain had several features that gave it a considerable, albeit temporary, advantage. Most importantly, Britain's political structure involved a meta-institution that was flexible enough to change and adapt to the new world. This function was filled by the British parliament, a place where different interest groups met, bargained and compromised within certain prespecified rules. Although considered a highly imperfect democratic institution by current standards, not least since it only represented the top layer of society (Mokyr, 2009, p. 414), the British parliament provided the type of agility that helped force socially beneficial decisions about new technology over potential losers with incentives to block the process.

The political economy of technological change and knowledge. In his analytical narrative, Mokyr offers many examples of how the process of creative destruction met with fierce resistance to technological change by vested interest groups. One example is the instance where tailors in Cologne, as early as 1397,

[15]Scholars writing about the gradually improved connection between science and technology in the 19th century have mostly argued for a causality running from technology to science (see, e.g., Rosenberg (1976, 1982)). Mokyr (2005a) argues in favour of seeing both science and technology as endogenous to the development of useful knowledge that occurred in Europe after the onset of the Enlightenment.

[16]This aspect of high-tail human capital was a driving cause in British leadership but has often been overlooked by economists focusing on the average schooling or skills in the workforce.

were prohibited from using machines that pressed pinheads; another is how the city council of Nuremberg, influenced by the guild of red-metal turners, launched an attack in 1561 on a coppersmith by the name of Hans Spaichl who had invented an improved slide rest lathe, threatening to put competitors out of business. Similarly, the inventor of the ribbon loom in Danzig in 1579 was reportedly secretly drowned by order of the city council, and in the 18th century, John Kay, the inventor of the flying shuttle for mechanized weaving, was harassed by unsettled weavers (Mokyr, 1990a, p. 178–179). There were also many examples of outright anti-machinery agitation, most famously the Luddite riots in 1811–1816 and the Captain Swing Riots of the 1830s, both of which took place in England (Mokyr, 1990a, p. 257). The comparative roles of resistance to new technology in Britain and France during the Industrial Revolution are assessed by Mokyr (1992), who further argued (Mokyr, 1994) that it is these barriers to technological change that account for the observed empirical regularity that no nation has managed to remain technologically creative for more than a historically short period of time, before being overtaken by a new technologically leading nation, a phenomenon referred to as Cardwell's Law.[17]

Similarly, the process connecting propositional and prescriptive knowledge often met with set-backs, time lags, and a large dose of creative destruction. In this process, resistance to new ideas did not only come from established interest groups, but sometimes also from scientists or practitioners; more famous examples include Tycho Brahe's denial of the Copernican system, Einstein's resistance to quantum theory, or James Watt's stubborn refusal to accept the workability of high-pressure engines, but many more instances are detailed by Mokyr (2002, p. 225–226). Yet, with an improved feedback loop between science and technology, new knowledge found a more effective way to transform society. The development of ideas for sterilizing surgical instruments—"one of the simplest and cheapest life-saving ideas in history" (Mokyr, 2002, p. 94)—provides an illustration. The idea is often attributed to Oliver Wendell Holmes and Ignaz Semmelweis in the 1840s, although similar thoughts can be traced back to the late 18th century. Initially, the idea that contaminated matter could be transmitted by physicians was, however, met with so much resistance that Holmes dropped it entirely and Semmelweis decided to leave Vienna in disgrace. It is argued that the opposition mainly came from medical practitioners who found the thought of themselves actively transmitting disease being somewhat of an insult, but another part of the problem was that neither Holmes nor Semmelweis could explain *why* new sanitary techniques could work. It was not until the 1860s and after the findings of Louis Pasteur and Joseph Lister that the ideas were revived. By then, the epistemic base of knowledge was larger, and statistical and experimental techniques were becoming more effective. By the late 1870s, sanitation recommendations became standard techniques.

2.4.3 Quantitative evidence

In collaborative work, Mokyr has provided a series of tests based on quantitative analysis supporting the core insights about the expansion of scientific knowledge, the practical applications and the connection between them.

[17] The struggle over technological change has thereafter been formally modelled in economics by, among others, Krusell and Rios-Rull (1996), Parente and Prescott (2002) and Acemoglu and Robinson (2006).

A joint evolution of science and technology. Mokyr collected a wealth of qualitative and quantitative evidence of the spread of the Enlightenment through various global institutions for knowledge transmission, such as The Republic of Letters—a long-distance intellectual community involving Europe and the Americas—and the emerging national scientific societies such as The Royal Society in Britain (chartered 1662), the French Academy of Sciences (founded in 1666), the Royal Swedish Academy of Sciences (founded in 1739), and many more.

Mokyr (2005a) traced the intellectual origins of the Industrial Revolution in an attempt to quantify the Enlightenment. Based on various sources mentioning enlightened ideas, scientific and technical journals and a database of scholarly societies, Mokyr documents a marked increase in publications and societies, as visualized in Figure 5.[18] Yet, Britain does not stand out as being unusually committed to, or engaged in, the Enlightenment movement. Thus, the quantitative evidence speaks in favor of viewing the Enlightenment as a pan-European phenomenon, gradually taking hold of many Western societies, albeit with different national styles and emphasis in the nature of knowledge spread and creation. Britain's advantage lay in its abundant supply of mechanical skills, an advantage that was extended during the Continental political upheavals of the Revolutionary and Napoleonic eras. However, European variations in adoption rates were a matter of differences in degree, not in kind. Because of the inherent characteristics of the pan-European Industrial Enlightenment movement, convergence of technology and income materialized with delayed European takeoffs in the 19th century.

Figure 5: Scientific periodicals by year of first appearance

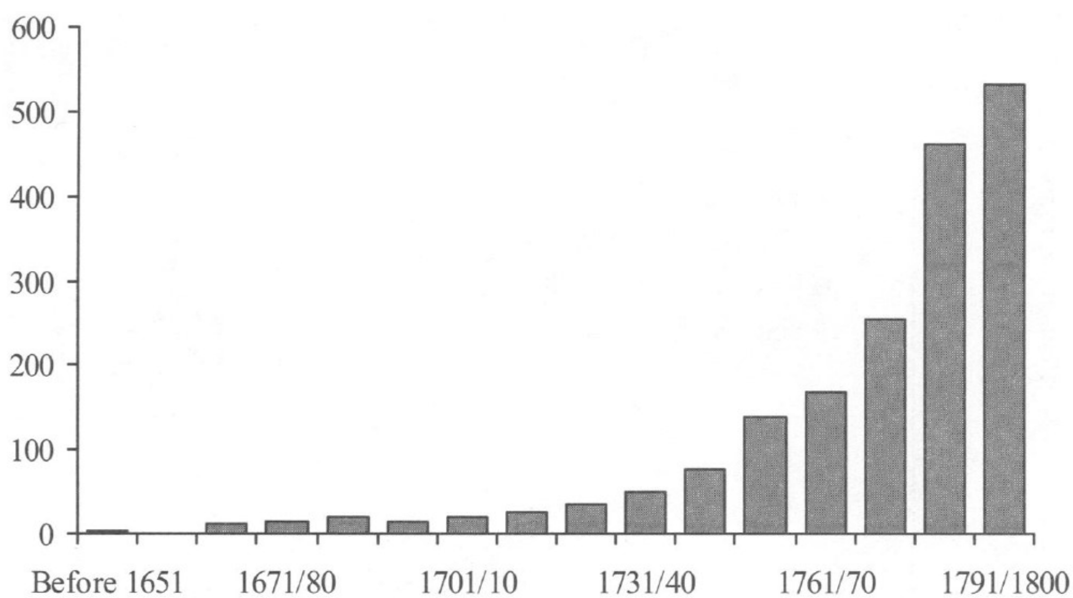


Figure notes: Scientific and technical journals published in Europe between 1600 and 1800, by year of first appearance. *Source:* (Mokyr, 2005a), based on Kronick (1991).

Evidence for the connection between scientific knowledge and practical implementation in Britain

[18]The data in Mokyr (2005a) is based on Kors (2003), Kronick (1991) and a database that relies heavily on the website "Scholarly Societies" collected by the University of Waterloo.

has been established in Meisenzahl and Mokyr (2012). The authors collected a new database of British inventors, tweakers and implementers representing successful careers in the early stages of British industrialization. The data were collected from different biographical compendia and cross-checked and complemented with information from the *Oxford Dictionary of National Biography* and the *Alphabetical Index of Patentees of Inventions* by Woodcroft (1854). It contains 758 men and one woman born before 1830 who contributed to technological change (the woman was Elenor Coade, who invented a new process for making artificial stone). To be in the sample, they had to have made some inventions themselves (mostly micro inventions and adaptations), but their main activity was tweaking and implementation. Thus, the focus here is not so much the famous inventors known from history text books, but rather the "tweakers" who were able to improve and de-bug existing innovations and the "implementers" capable of building, installing and operating new and complex equipment. Such engineers, mechanics, millwrights, chemists, clock- and instrument makers, skilled carpenters and metal workers constituted the top level of skills-distribution just below the layer of the most famous inventors. With this data, Meisenzahl and Mokyr (2012) showed that new inventions occurred in a broad set of sectors, not just in textiles and metals, and that many inventors were engaged with the scientific community. Above half of the inventors in the sample either published in, or belonged to, scientific or technical societies, and among those more narrowly defined as engineers, the corresponding figure was around two-thirds. However, only 10% of the inventors in textiles, the traditional focus industry of the Industrial Revolution, engaged with such professional societies. The authors also show how the upper-tail human capital among these inventors were formed, as about two-thirds of the tweakers had been apprenticed. However, despite having contributed to important innovations, 40% never took out a patent. With this data, Meisenzahl and Mokyr (2012) concluded that an Enlightened culture was rooted in the top of the skill distribution, and that apprenticeship rather than years of formal schooling played important roles.

Mechanical competence. In understanding Britain's early advantage over other countries in mechanical competence, two factors stand out: (i) early advantages in metal trades and water-powered machinery, and (ii) an unusually flexible apprentice system that allowed for knowledge creation and industrial applications. Relating to the first, Mokyr et al. (2022) go back to data from the Domesday Book in 1086 to trace the origins of mechanical skills to the adoption of water-powered mills. They argued that the millwrights' growing competence in construction, maintenance and improvement of the machinery generated an early local advantage for complementary machinery in other industrial uses at the same site. Relating to the second, Mokyr, together with coauthors Kelly and Ó Gráda showed that British laborers in 1750 were far superior to those on the Continent in terms of both physical qualities and technical skills (Kelly et al., 2014). They highlight that while Britain did have higher wages than France, these differences in wages actually reflect differences in human capital and skill. In other words, the English workers were more productive than the French.[19]

Finally, a first effort to qualitatively evaluate the many competing explanations for the Industrial Rev-

[19]Using annual information on apprenticeships in England between 1710 and 1805 and Vector Autoregression (VAR)-techniques, Mokyr with co authors Zeev and van der Beek also found evidence of an elastic supply of apprentices, sufficiently high to allow a considerable response to demand shocks (Zeev et al., 2017).

olution was made by Mokyr with coauthors Kelly and Ó Gráda (Kelly et al., 2023). The authors collect data on key variables, including measures of mechanical skills and wages, from 41 English counties between the 1760s and 1830s. Using this data, they examine whether a wide range of factors—wages, artisan skills, access to coal, literacy, financial markets and legal capital—were decisive in early industrialization, and they find that industrialization occurred in areas that began with low wages but high mechanical skills, whereas other variables, such as literacy, banks and proximity to coal, have little explanatory power. Figure 6 demonstrates one of the main takeaways from their data. It plots each county's textile employment share in 1851 against the mechanical skills in the 1790s (on the left) and the agricultural wages in 1760 (on the right). There is a positive relationship between the pre-Industrial Revolution supply of mechanical skills (measured in the census of 1851 as the share of men over 60 with occupations such as blacksmiths, millwrights, watch- and instrument makers, gunsmiths and locksmiths, toolmakers, sheet-metal workers, and mechanics) and the share of workers in textiles 1851. On the other hand, the relationship with wages is negative.[20]

Figure 6: Mechanical skills, wages and industrialization in English counties

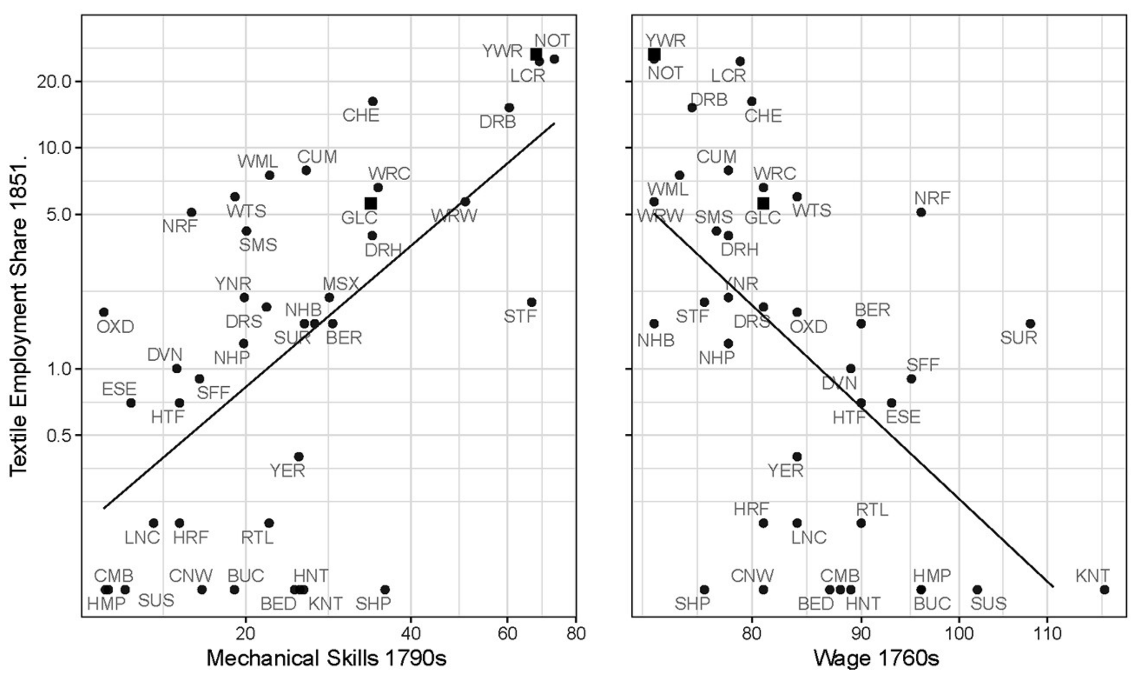


Figure notes: Left panel: The supply of mechanical skills vs. percentage of males employed in textiles 1851. Right panel agricultural wages in the 1760s vs. percentage of males employed in textiles 1851, logarithmic axes. *Source:* Kelly et al. (2023).

[20] These findings are also supported in ordinary least squares (OLS) regressions, which can control for other factors such as market potential and access to coal, as well as the competing stories highlighted above. The results are also robust to specifications that deal with the potential endogeneity of the skill supply—namely that the presence of new industries could have resulted in the in-migration of skill—by instrumenting for skill with the median fee to become an apprentice watch maker in the 1700s. Evidence for the competing, but not mutually exclusive, hypothesis that labor scarcity and high wages were conducive to technology adoption and innovation by, e.g., Allen (2009), has been found by Voth et al. (2023), who document synergies between labor shortages and local skill supply, which combined further increased technology adoption and the rate of productivity improvement along the lines of Kelly et al. (2023).

2.5 Empirical follow-up studies

Connecting the scientific and industrial revolutions, Kelly and Ó Gráda (2022) showed how the diffusion of numerical skills supplied Britain with a pool of mechanically skilled labor to build the increasingly complicated machinery of the late 18th century. They also showed that the revolutionary innovations in machine tools drew on a technology of exact measurement developed for navigational and astronomical instruments. Figure 7 establishes that strong connections between science and technology led to the success of the English instrument industry relative to its less adaptable French counterpart. A similar connection to the spread of useful knowledge has been quantitatively established in Galofré-Vilà (2023) who found that British counties with a relatively high number of informal networks—in the form of Freemasonry, friendly societies, libraries, and booksellers—experienced more innovation as measured by new patents or exhibits at the 1851 Crystal Palace World's Fair.

Across Europe, Squicciarini and Voigtländer (2015) found that the Enlightenment reduced costs of accessing useful knowledge and influenced economic growth in 18th and 19th century France, and Cinnirella et al. (2024) found that economic societies led to more innovative activities in 19th century Germany. Although the focus on France and Germany does not permit the authors to say anything about the origins of the British Industrial Revolution, these studies test the main idea about the Enlightenment being a pan-European phenomenon influencing useful knowledge and economic growth, once other barriers were removed.

Figure 7: Number of instrument makers by decade

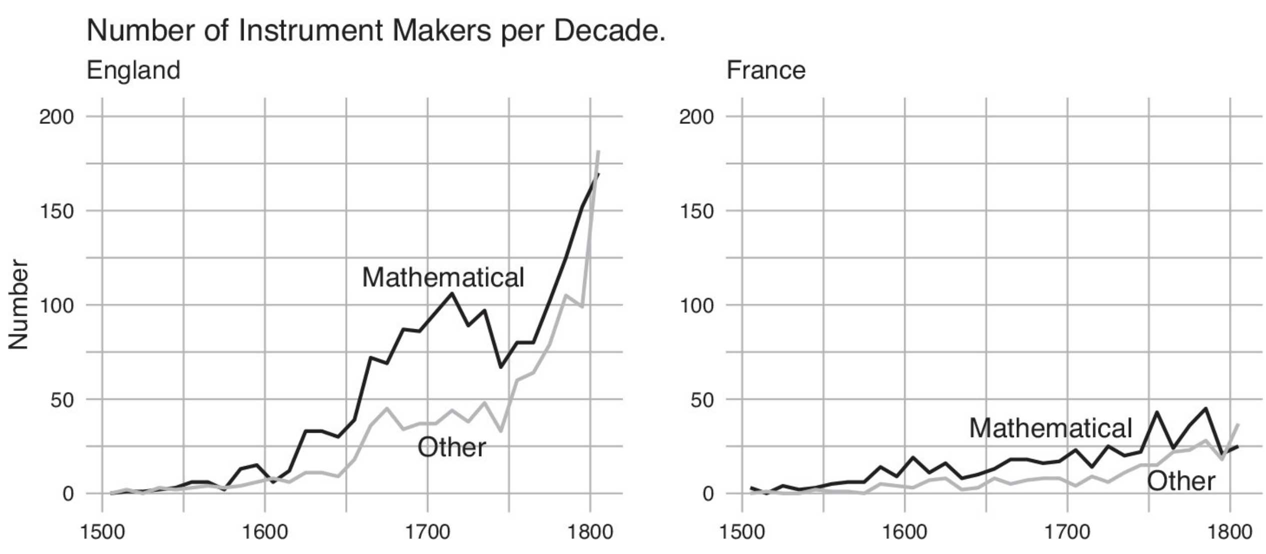


Figure notes: Known English and French makers of mathematical and other instruments by decade. *Source:* Kelly and Ó Gráda (2022) building on the Webster Signatures Database.

Studies by De Pleijt et al. (2020), and Hanlon (2025) have further quantitatively established the role of skilled workers and engineers sustaining the British Industrial Revolution, whereas the role of engineers in global economic growth has been documented for the U.S. (county-level) and at national levels for the

Americas during the Second Industrial Revolution (1870–1914) by Maloney and Valencia Caicedo (2022).

Finally, few quantitative studies document causal evidence of popular resistance on technological change. An exception is Caprettini and Voth (2020), who collect data on threshing machine diffusion and show that labor-saving technology was associated with more riots among agricultural workers in England during the 1830s.

2.6 Scientific impact

History is rarely monocausal. It is likely that several causes for main events can be present at the same time. Different theories, moreover, are not necessarily contradictory but, rather, complementary. The debate about the Industrial Revolution and its causes is broad and abounds with alternative factors and explanations. It is probable that many conditions interacted to create the specific chain of events unfolding when Britain emerged as the world's first industrial nation. Today, however, it is widely accepted that any explanation for a sustained acceleration of productivity growth must come from "understanding the development and subsequent incremental improvement of new technologies" (Crafts, 2011, p. 166).

With a novel framework that put technology at the center, Mokyr changed how the field viewed the onset of modern economic growth. Instead of seeing technology as the residual from everything we can measure (e.g., Solow (1957)), Mokyr introduced a new perspective, focusing exactly on explaining technology and the necessary requirements needed for technology to feed into sustained growth. By emphasizing the broad societal and technological changes that took place during and after the Enlightenment, Mokyr's work reintroduced the "revolution" into the Industrial Revolution. Contrary to those seeing the period as a gradual structural transformation, Mokyr emphasized the transformational character of growth rates that were sustained over the longer run, even though their magnitudes were at first sluggish. Pioneering and documenting the resistance to technological change, Mokyr also integrated the political economy of technological change into the historical debate, and stimulated further economic models in this vein.

Mokyr's novel explanation went beyond the combination of existing growth theories, and the common search for country-specific factors. Aiming to account both for the long-term pre-industrial stagnation, as well as the timing and place of the Industrial Revolution, his work connected economic history with history of technology and science and shifted the focus from country-specific pre-conditions to global comparisons. In focusing on relevant macro comparisons between Western Europe and China, Mokyr was ahead of his time. Many comparative ideas were later developed and discussed by the so-called California School, which challenged conventional views on the Great Divergence and emphasized the need for a more global and contextual approach to economic history (see for example Frank (1998), or Pomeranz (2000)).

The macro comparisons and fundamental questions asked by Mokyr have influenced several fields in economics, such as development economics, growth theory, and macroeconomics who have benefited from integrating large ("Big Think") arguments into their studies. As a result, undergraduate and graduate courses in economics now include books and papers that discuss Mokyr's ideas in their curricula and recent work on how various aspects of long-run growth relate to and engage with his work (see for example Johnson and Acemoglu (2023) or Aghion et al. (2021)). In recent standard textbooks, Mokyr's work is a main reference on the topic of Industrial Revolutions and the causes of sustained modern economic growth (see for example Blum and Colvin (2018), Persson and Sharp (2025), or Koyama and Rubin (2022)).

3 Creative destruction and growth

While Mokyr studied the takeoff of growth during the Industrial Revolution and the lack of sustained growth prior to this event, Aghion and Howitt were motivated by the remarkably stable nature of aggregate growth in advanced economies over the post World War II period. Aghion and Howitt also noted that technological change is a very disruptive process in which successful innovators enter new markets or expand their production, but do so by making older products obsolete and by (partially) stealing business from incumbent firms. Hence, Aghion and Howitt's analysis was motivated by how they perceived innovation to actually take place, and to this end, they set out to provide a theoretical framework for studying this process.

It was far from obvious whether and how an endogenous growth theory that features business stealing, creative destruction, and entry and exit at the micro level can be squared with the remarkably balanced picture of growth at the aggregate macro level. Aghion and Howitt (1992) reconciled the seemingly contradictory micro and macro observations and demonstrated how the theory could be used to address normative policy questions. The 1992 paper marked a paradigm shift in the growth literature. At its core, the theory features a rich interplay between competition and innovation, which allowed Aghion and Howitt to connect the literature on macroeconomic growth with the field of industrial organization—a connection that proved to be extremely fertile.

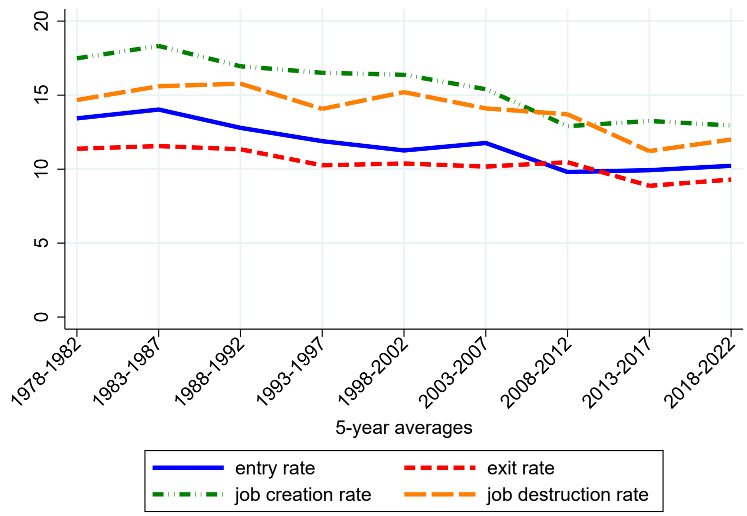
The model Aghion and Howitt constructed had a number of predictions for firms that were borne out in the data; the theory also turned out to be amenable to countless extensions and generalizations, thereby generating a large amount of follow-up research. Below, we begin by motivating the concept of "creative destruction" empirically and showing how it is linked to economic growth. We continue by commenting on the point of departure in the literature to which Aghion and Howitt's work belongs. We then lay out the basic theoretical mechanism and comment on empirical follow-up studies and the policy relevance of their work.

3.1 Motivating evidence

Advanced economies are very dynamic, i.e., growth goes hand in hand with the continuous process of entry, exit, and churning of production factors across production units. The theory by Aghion and Howitt (1992) makes a connection between this disruptive process and the aggregate growth rate of technological change. In this section we document in U.S. micro data the scale of this process of creative destruction and how it is connected to growth—the main study object of Aghion and Howitt (1992).

Figure 8 shows firm entry and exit rates and the rates of job creation and destruction in the U.S. In a typical year more than 10% of firms either enter or exit the market. The reallocation rate of production factors across establishments—measured in Figure 8 as job creation and destruction rates—is high too, suggesting a continuous reallocation of jobs among incumbent firms.

Figure 8: Dynamism in the U.S.



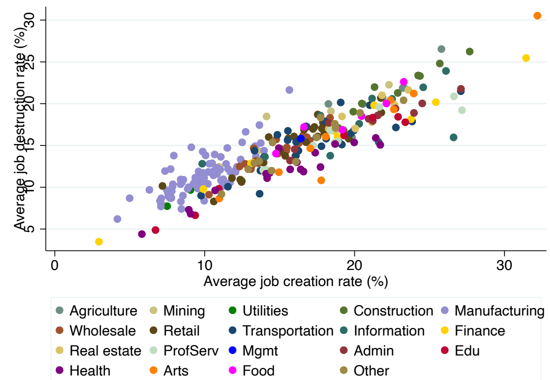
Data Source: Business Dynamics Statistics. The figure shows 5-year averages of the annual firm entry, firm exit, and job creation and destruction rates in percent. The green line shows the job creation rate, i.e., the number of jobs created by entering or expanding establishments relative to the total number of jobs. The orange line is the average annual job destruction rate, i.e., the number of jobs "lost" by exiting or shrinking establishments relative to the total number of jobs.

The vast majority of the churning happens within narrowly defined industries as opposed to being associated with a secular shift of economic activity between sectors (see Davis and Haltiwanger (1992) and Davis et al. (1996)). Figure 9 shows the correlation across 4-digit industries between various measures of dynamism averaged over the years 1980–2022. In industries where the firm entry rate is high, the firm exit rate is high too (see Figure 9a). Industries that show a high rate of job destruction also show a high rate of job creation (see Figure 9b). Figure 9c documents a positive correlation of firm entry rates with the establishment exit rate. This moves us closer to the notion of a product cycle, as the closing down of an establishment may be viewed as a proxy for product market exit.[21] Finally, Figure 9d shows that a higher firm entry rate is not only associated with higher exit but also with a higher job destruction rate for surviving incumbents. The literature has documented a range of additional empirical facts beyond the patterns shown here, e.g., that exit rates fall with firm age, that plants and firms grow in size over their lifecycle conditional on survival, and the large differences in firm size within narrowly defined industries (see Haltiwanger et al. (2013), Decker et al. (2014), and Hsieh and Klenow (2014)). These facts are also well established in economies other than the U.S. (see Bartelsman and Doms (2000), Ahn (2001), and Bartelsman et al. (2004) for survey evidence).

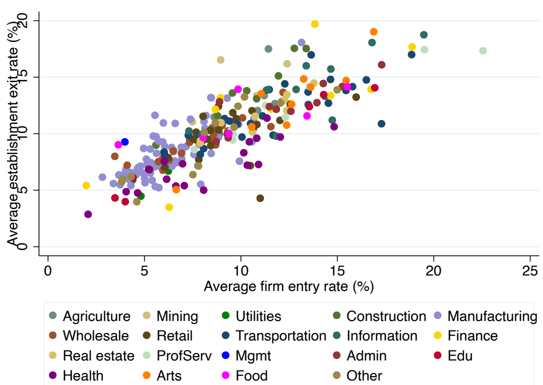
[21] Bernard et al. (2011) show that manufacturing firms that add establishments also branch out into new industries. For services, Hsieh and Rossi-Hansberg (2023) show that the addition of establishments, which is prominent, allows a firm to penetrate more (local) markets.

Figure 9: Measures of dynamism across U.S. industries, 1980–2022

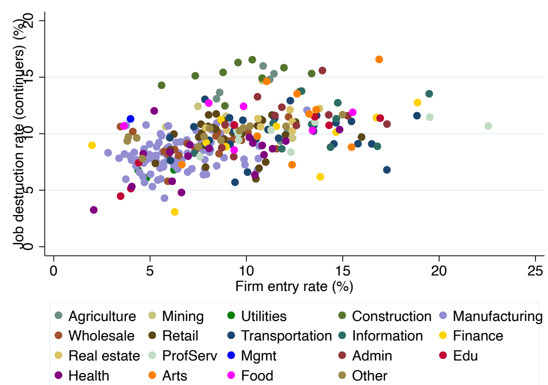
(a) Firm entry vs. exit



(b) Job creation vs. destruction rate



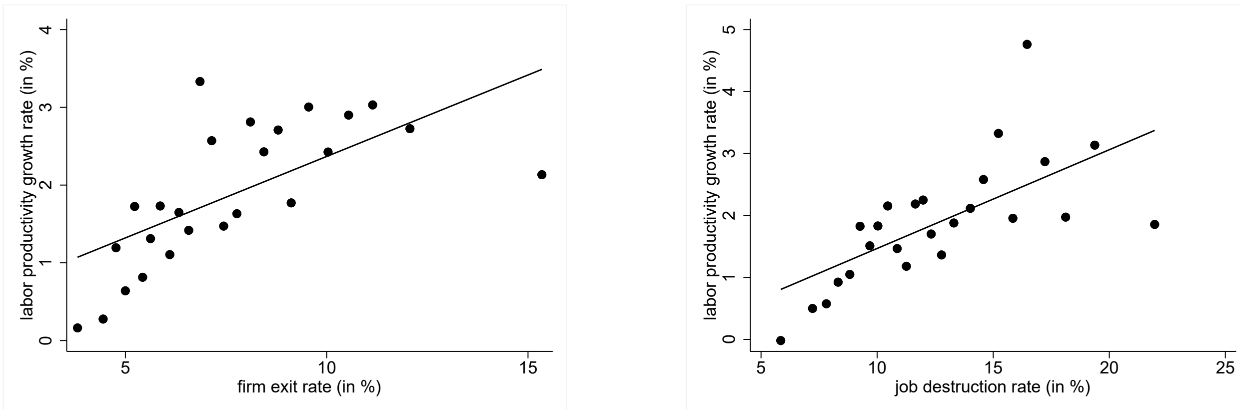
(c) Firm entry vs. establishment exit



(d) Entry vs. job destruction by incumbents

Data source: Business Dynamics Statistics. The sample consists of different four-digit industries. Different two-digit sectors are highlighted by different colors.

Figure 10: Labor productivity growth vs. measures of dyanamism, 1988–2022



(a) Firm exit rate

(b) Job destruction rate

The figures show binned-scatter plots of 5-year averages by industry in firm exit rates or job destruction rates vs. the 5-year averages of labor productivity growth rates. The sample consists of 159 four-digit industries and seven 5-year periods. The figures are inspired by a similar analysis in Adhami (2025). *Data source:* Business Dynamics Statistics for dynamism variables and BLS for labor productivity growth.

The empirical appeal of the creative destruction paradigm is that it not only speaks to the evidence on firm dynamics but connects the facts in Figure 9 to growth and technological change. Figure 10 shows, in binned scatterplots, that both the 5-year-industry average in firm exit rates and the job destruction rates are positively related to labor productivity growth.[22] Foster et al. (2001) and Bartelsman and Doms (2000) attribute about one quarter of average total factor productivity growth to entry and exit—and this number is estimated to be even higher in Lentz and Mortensen (2008)—while the remaining productivity improvements are accounted for by continuing plants. Garcia-Macia et al. (2019) use various moments of job reallocation across firms as well as entry and exit rates, to infer the contributions of different types of innovations; based on the data, they argue that creative destruction plays an important role. Finally, Baqaee and Farhi (2020) calculate that roughly half of aggregate U.S. total factor productivity growth over the period 1997–2015 is due to the reallocation of production factors from low to high revenue productivity firms.

Even at the aggregate time series level, measures of dynamism (i.e., entry, exit, and rates of job churning) are correlated with economic growth in the U.S. and in other advanced economies. Figure 8 reveals a pattern of declining dynamism since the mid-2000s.[23] This period is indeed characterized by a productivity growth slowdown; more recent literature connects the two phenomena through the prism of creative destruction (see, e.g., Decker et al. (2016), Akcigit and Ates (2021), Aghion et al. (2023), and Akcigit and Ates (2023)).

In Section 3.3 we present the basic theory of growth through creative destruction as introduced by

[22]Appendix Figure A2 shows similar correlations of other measures of economic dynamism with labor productivity growth.

[23]Calvino et al. (2016) document a comparable declining dynamism in countries other than the U.S. and the harmonized data of 20 countries going back to the year 1998 can be found here. Furthermore, the CompNet platform, that can be found here, provides comparable statistics for 17 European countries.

Aghion and Howitt (1992). Before we do so, we comment on how their contribution is embedded in the literature.

3.2 Points of departure

The observation that economic growth of advanced economies is ultimately driven by technological change as opposed to factor accumulation goes back to at least Solow's work (Solow, 1956, 1957). As a consequence, much research has followed Solow's original contribution, and focused on how to measure technological change and how economies accumulate physical and human capital as a result of technological change.

The question of what drives technological change itself was not formally addressed until the early 1990s, when Paul Romer began to formulate theories around knowledge accumulation through purposeful innovation and emphasized key attributes such as the non-rival nature of ideas (see Romer (1990)). Older versions of endogenous growth models were instead solely based on physical and human capital accumulation, with the potential addition of externalities (see Romer (1986) and Lucas Jr (1988)). The theoretical literature that connects the aggregate growth rate to purposeful R&D investments took longer to emerge because it is far from obvious how competitive forces play out in the market for ideas, such as blueprints for new products, and how this process can be modeled in general equilibrium. A key theoretical building block that allowed the innovation-led growth literature to take off was marked by the framework of monopolistic competition (Dixit and Stiglitz (1977)). Romer modeled the rate of technological change as the addition of new product varieties that complement all preexisting products. But major theoretical obstacles remained, and in its infancy, the literature on innovation-led growth remained rather theoretical and abstract; its efforts were arguably mainly driven by intellectual curiosity and conceptual challenges.

Aghion and Howitt were at the forefront of this early literature, but were motivated by the additional observation that at the more microeconomic level, i.e., the industry, firm, and product level, growth is not balanced at all. The process is instead characterized by a highly disruptive nature with entry, exit, and churning (see Section 3.1). In reality, innovations do not magically lift all boats but—despite being overall socially beneficial—systematically generate winners and losers. By explicitly modeling the disruptive nature of growth and technological change, where successful innovations replace older products and destroy the rents of incumbent firms, Aghion and Howitt (1992) introduced the notion of creative destruction into the theoretical literature on endogenous growth and showed how it still can be squared with a sustained balanced growth path in the aggregate.

The concept of creative destruction is also tightly linked to Joseph Schumpeter, who described the relentless innovation and entry of new entrepreneurs as the key driver of aggregate growth (see in Schumpeter (1942)).[24] In sharp contrast to Schumpeter, who saw creative destruction as the seed of an inevitable demise of free-market economies, Aghion and Howitt demonstrated how creative destruction-

[24] The Schumpeterian ideas have sparked a rich literature and several schools of thought in economics and neighboring disciplines, for example the evolutionary or neo-Schumpeterian schools (e.g., Nelson and Winter (1982)). The main aspect discussed here focuses more narrowly on the ideas of how the process of creative destruction can be formalized as the driver of sustained economic growth in the aggregate.

driven growth can actually be sustained, and not slow down, as had been the case before the Industrial Revolution.

In parallel, Segerstrom et al. (1990) characterized a model with some features in common with the model of Aghion and Howitt (1992)—innovations build on each other and therefore eclipse previous ones—and applied the model to study international trade between poor and rich countries.[25]

The paper by Aghion and Howitt (1992) was key in opening up the field by establishing the creative destruction paradigm and demonstrating its potential for both positive and normative analyses of aggregate growth. The resulting framework turned out to be amenable to extensions, was quickly adopted (see, e.g., Grossman and Helpman (1991b) for an early adoption), and generated a large body of literature that followed in Aghion and Howitt's footsteps.

Aghion and Howitt built on the industrial organization literature on patent races (see, e.g., Loury (1979), Lee and Wilde (1980), and Reinganum (1985)). Unlike Romer (1990), this literature typically models innovations to be uncertain and to be substitutes rather than complements to each other, such that a successful innovation eclipses the effort of a competitor. A key theoretical challenge Aghion and Howitt overcame was to incorporate the mechanisms studied in industrial organization—which rely on strategic interactions—into general equilibrium. How can the conflicting interests be squared with the remarkably balanced picture of growth at the aggregate level? Aghion and Howitt provided an answer in their 1992 paper, used the framework to discuss normative questions, and extended the mechanism to capture strategic interactions in follow-up work (see Aghion et al. (2001)). As a result, Aghion and Howitt's contribution has allowed the macroeconomic literature on growth to be merged with the industrial organization literature on R&D and competition.

3.3 A basic framework of growth through creative destruction

This section specifies the basic framework of growth through creative destruction as introduced by Aghion and Howitt (1992). We first outline the so-called firm problem in partial equilibrium and show how the future threat of creative destruction influences the value of an incumbent firm. We then illustrate how this building block can be integrated into a general equilibrium analysis to explain the long-run growth rate of the aggregate economy. Finally, we contrast the decentralized equilibrium with the so-called planner's solution in order to comment on policy.

3.3.1 The profit and value function of a monopolist in partial equilibrium

Consider a monopolist with a perpetual patent to produce a good ν at a quality level $q(\nu)$. Suppose that, in each period t, the downward-sloping demand function for the good reads as follows

$$y_t(\nu) = q_t(\nu)\, p_t(\nu)^{-\frac{1}{1-\alpha}}\, L, \tag{1}$$

[25] Grossman and Helpman (1989) provided another related theory of the role of product cycles for patterns of international trade.

where $p(\nu)$ denotes the price of good ν and we have $\alpha \in (0,1)$. Equation (1) postulates that the demand for a product ν is increasing in its quality and decreasing in its price. The parameter $L > 0$—which will later in the general equilibrium version be related to total employment in the economy—can be viewed as pinning down the level of demand.

Assume further that a production technology allows the monopolist to translate α units of a final output good into one unit of output of good ν. If we normalize the price of the final output good to one, so that $p_t(\nu)$ is the number of final output goods needed to buy one unit of good ν, the costs of producing $y_t(\nu)$ units of the good will be $\alpha y_t(\nu)$. Given these assumptions, the monopolist's production decision is a simple static problem: each period, the output level and prices are chosen to maximize period profits and the future does not influence this decision. Formally, profits π in any period and for any good (where we drop time and goods indices whenever it does not lead to confusion) are then given by:

$$\pi(q) = \max_{y,p} \{yp - \alpha y\}, \quad \text{subject to} \quad (1). \tag{2}$$

This yields the following equilibrium price, quantity, and profits: $p = 1$, $y = qL$, and $\pi(q) = (1-\alpha)qL$. These objects are all time-invariant, as we assume that the monopolist produces at a fixed level of quality q. But in the cross-section, firms that produce at a higher quality level do make higher profits.

The market value of a monopolist producing at quality q is given by the expected discounted sum of all future profits. We assume for simplicity that the interest rate is constant and equal to $r^\star > 0$. The expected discounted sum of profits is uncertain because in each period the firm faces a constant probability $z^\star \in (0,1)$ that a competitor innovates in the same product market and destroys the rent of the incumbent firm (i.e., the previous incumbent makes zero profits from then onward). Under these assumptions, the value of the incumbent firm can be stated in recursive form as

$$v(q) = \pi(q) + \frac{1}{1+r^\star}\left(z^\star \cdot 0 + (1-z^\star) \cdot v(q)\right). \tag{3}$$

That is, the expected firm value today is equal to profits plus the expected continuation value discounted by the interest rate. The expected continuation value takes into account that the incumbent is toppled with probability $z^\star$. Equation (3) can be solved for $v(q)$ to yield

$$v(q) = (1+r^\star)\frac{(1-\alpha)L}{r^\star + z^\star}q, \tag{4}$$

where we made use of the equilibrium value of profits $\pi(q) = (1-\alpha)qL$. The interest rate and the rate of creative destruction $z^\star$ are taken as given by the incumbent firm but are endogenously determined in the model through general equilibrium forces (see below where we also rationalize the constancy of the interest rate and the rate of creative destruction along a balanced growth path).

The main new element in this basic model of creative destruction is given by the $z^\star$ term in the firm value (4). This term captures the effect of future innovations on the value of an incumbent firm. A successful innovation destroys the rent of an incumbent firm and leads to exit. As a consequence, the incumbent firm's value decreases in the rate of innovation $z^\star$, i.e., future creative destruction is a threat to the incumbent firm.

Innovation. Suppose a potential entrant can come up with a successful innovation in the product market with probability $z = x\psi/q$, where x denotes the resources the entrant spends on R&D (measured in final output goods) and $\psi > 0$ is a parameter measuring R&D productivity. Here the formulation assumes that innovations become (proportionally) more costly, the higher the incumbent's quality level. If an innovation is successful in period t, the innovator obtains the knowledge and a perpetual patent, from period $t+1$ onward, to produce at new quality $\gamma \cdot q_t$, where q_t refers to the quality of the producer in period t. Hence an innovation improves the quality of a product by a (step size) factor $\gamma > 1$.[26] In this model, innovations increase the quality of a preexisting product. As a consequence, an innovation allows a new entrant to produce in a given line with a strictly "better" technology (i.e., at higher quality), making the technology of an incumbent firm obsolete and leading to exit. Note also that the threat of creative destruction is inherent in the way technological change takes place, i.e., a patent cannot ensure an incumbent firm against the risk of seeing its rent creatively destroyed. In fact, the replaced incumbent still holds a patent to produce at a particular quality level, but this patent is worthless.

Another important feature of the modeling of technological change is that innovations build on past innovations. This is sometimes referred to as the "standing on the shoulders of giants" effect. In other words, innovations do not have to start from scratch, but rather take an existing product or process and improve it by an incremental γ step. This implies that the model features knowledge spillovers from past to new innovators that allow the innovation process to be self-propelling. This knowledge spillover is not fully internalized in the decentralized market equilibrium, as firms only care about the profits they can make while they are the incumbent.

With free entry into R&D (and strictly positive innovation activity), the cost of spending one unit of final output on R&D must equal the discounted expected firm value of a quality level γq from next period onward, i.e., we must have $1 = (\psi/q)v(\gamma q)/(1+r^\star)$. We have the firm value $v(\gamma q)$ in this expression because a firm that innovates today in a product line with quality q will receive a patent to produce at quality γq from tomorrow onward. With the firm value in (4), the condition above simplifies to

$$r^\star + z^\star = \gamma\psi(1-\alpha)L, \tag{5}$$

where $z^\star$ again denotes the rate of creative destruction. This demonstrates that if the interest rate is constant, the equilibrium rate of creative destruction $z^\star$ is indeed constant over time too. Note, however, that a constant $z^\star$ implies a constant innovation probability, and the innovation realization in a given product line is therefore a random variable. Aghion and Howitt (1992) studied, among other settings, a version of such a model where the aggregate economy consists of a single product line and showed that it can lead to growth cycles (the economy alternates between high and low growth periods). In the next section, we instead integrate this building block into a setting in which the aggregate economy consists of a continuum—a unit interval—of such product lines. With this assumption, the stochastic nature of

[26] To ensure that so-called "drastic innovations" take place, we make the additional assumption that $\gamma > \alpha^{-\frac{\alpha}{1-\alpha}}$. The case of "non-drastic" innovations is discussed further below.

individual product lines is smoothed out at the aggregate level (see Grossman and Helpman (1991a), or Acemoglu (2008) and Aghion et al. (2014) for textbook-like treatments).[27]

3.3.2 Creative destruction in general equilibrium

Aghion and Howitt (1992) integrate the basic mechanism above into a general equilibrium setting, where the rate of creative destruction and the interest rate are jointly explained by supply and demand. Here we illustrate how this can be accomplished.

The demand schedule (1) that we postulated above in the basic framework can be micro-founded by assuming a final output good that is competitively produced according to

$$Y_t = \frac{1}{\alpha} L_t^{1-\alpha} \int_0^1 q_t(\nu)^{1-\alpha} y_t(\nu)^{\alpha} d\nu, \tag{6}$$

where L_t denotes labor used in final production and there is a unit interval of intermediate inputs (for which the quality can be improved by innovations). Then, for each product line ν, the static partial equilibrium analysis from above follows. The aggregate production function (6) can be viewed as a Cobb-Douglas production function over labor and a constant elasticity of substitution (CES) bundle of a unit interval of intermediate products (which come at a particular quality q). The aggregate production function features constant returns to scale in all inputs (labor and intermediate products), and the CES structure over the different intermediate products allows for the modeling of monopolistic competition as proposed by Dixit and Stiglitz (1977).

We indicated above that R&D is carried out using the final good; this formulation is often called the lab-equipment version. We thus assume that the final output good is not only used in intermediate goods production and for final consumption purposes but also for R&D. The resource constraint is therefore given by

$$Y_t = C_t + X_t + E_t, \tag{7}$$

where $E = \int_0^1 \alpha y(\nu) d\nu$ is total resources spent on intermediate good production, C denotes consumption, and $X = \int_0^1 x(\nu) d\nu$ is total resources spent on R&D. Furthermore, a labor market clearing condition states $L_t = L$ (where L is constant exogenous labor supply).[28]

Substituting the equilibrium quantity $y(\nu) = q(\nu)L$ into (6) allows us to write

$$Y_t = \frac{L}{\alpha} Q_t, \tag{8}$$

where we define $Q_t \equiv \int_0^1 q_t(\nu) d\nu$ as the "average quality." Output is proportional to Q_t and in this model all growth is driven by quality improvements. In the following, we assume that there is a balanced growth path with a constant interest rate $r^\star$ and then show—by solving the so-called household problem—that such a constant $r^\star$ is indeed supported. Note that the firm problem above implies an equilibrium $z^\star$ that

[27] As the framework above is cast in discrete time one has to rule out that more than one innovation will occur in the same product market during the same time period. Large parts of the theoretical growth literature are therefore specified in continuous time, where the probability of two innovations taking place at the same instant is zero.

[28] Howitt (1999) provides an endogenous growth model through creative destruction that explicitly allows for population growth.

is not product line specific; i.e, if the interest rate is constant, the rate of creative destruction is constant over time and across lines ν. Hence, each period, an innovation occurs in a fraction $z^\star$ of all the ν lines. With a successful innovation, the quality increases by a factor γ and the gross growth rate of Y is therefore

$$g^\star \equiv \frac{Y_{t+1}}{Y_t} = \frac{Q_{t+1}}{Q_t} = (1 - z^\star) \cdot 1 + z^\star \cdot \gamma = 1 + z^\star(\gamma - 1). \tag{9}$$

This relates the constant (gross) growth rate of the economy $g^\star$ to the rate of creative destruction $z^\star$ and the step size of innovation γ. We close the model by assuming a representative household maximizing the utility function, $\sum_{t=0}^{\infty} \beta^t \log(C_t)$, subject to standard constraints.[29] Intertemporal household optimization results in the following consumption Euler equation $C_{t+1}/C_t = \beta(1 + r_{t+1})$. As E and X grow at the same gross rate $g^\star$, the gross growth rate of consumption has to be equal to this rate too (see (7)); i.e., we have $g^\star = C_{t+1}/C_t$, $\forall t$. Hence, the Euler equation implies that the interest rate indeed has to be constant. Combining the Euler equation with (5) and (9) allows us to finally characterize the equilibrium rate of creative destruction as a function of exogenous parameters:

$$z^\star = \frac{\gamma\beta\psi(1 - \alpha)L - 1 + \beta}{\gamma - 1 + \beta}. \tag{10}$$

This expression shows how the rate of creative destruction is influenced by all the primitive parameters of the model in our decentralized equilibrium. All other equilibrium outcomes then follow immediately; e.g., the aggregate growth rate of the economy is just a monotonic transformation of the rate of creative destruction (see (9)).

Discussion. This basic model of creative destruction directly generates implications for entry, exit, and a stochastic firm lifecycle, and therefore generates firm heterogeneity. The probability of a successful innovation can be influenced by the R&D investment decision, but innovation remains a stochastic outcome. Some incumbent firms will be lucky and stay in business for a long time, whereas others are quickly creatively destroyed and disappear. At its core, the framework features a conflicting interest of (potential) entrants and incumbent firms. Intellectual property rights in the form of patents do not shield an incumbent firm from the threat of creative destruction, but blocking entry does. As the rate of creative destruction a firm faces in the future decreases its value, an incumbent firm has an incentive to lobby for a policy that makes entry or R&D activity harder.

Why don't incumbent firms themselves instead use R&D investments to prevent being creatively destroyed by climbing the quality ladder? If they did, they would only reap the benefit of the increment $\gamma - 1$ to their value, which would not allow them to recover the R&D expenses, as we have $(\gamma - 1)(\psi/q)v(q)/(1 + r^\star) < 1$.[30] This is a manifestation of the so-called Arrow replacement effect (see Arrow (1962)): incumbents have less to gain from innovating in their product lines than do new entrants, as they would then partially cannibalize their own profits.[31]

[29] To ensure the existence of an interior solution to the decentralized equilibrium conditions, we need to have $\gamma\psi(1-\alpha)L > 1/\beta - 1$ and $1 > \beta\psi(1 - \alpha)L$, which we assume to hold in the following.
[30] To arrive at this expression we used the property $v(\gamma q) = \gamma v(q)$ (see (4)).
[31] Below we comment on important extensions of the basic framework that do generate a motive for incumbent firms to improve

3.3.3 Planner's solution

Aghion and Howitt (1992) leverage the novel framework of creative destruction to also study normative questions. We therefore derive the optimal growth rate a social planner would choose. From a planner's perspective, and indeed the representative consumer's perspective, there are no conflicts. This is because consumers own all the firms and the conflicting interests between firms do not matter per se; what matters is simply final consumption that is realized over time, and the utility consumers derive from it.

It is easy to show that, in the framework above, a social planner produces a quantity $y(\nu) = q(\nu)\alpha^{-\frac{1}{1-\alpha}}L$ of each intermediate input. This is the demand that would prevail if each input is priced according to marginal cost α—see (1). With this, we can write output net of intermediates as

$$Y_t - E_t = (1-\alpha)\alpha^{-\frac{1}{1-\alpha}}LQ_t, \tag{11}$$

where Q_t is average quality as defined above. The planner has no reason to choose heterogeneous zs across different lines. Under such symmetry, we have $X_t = z_t/\psi \int_0^1 q_t(\nu)d\nu$, and the resource constraint allows us to express

$$C_t = \left((1-\alpha)\alpha^{-\frac{1}{1-\alpha}}L - z_t/\psi\right)Q_t. \tag{12}$$

After substituting this expression for C_t into the utility function, we can state the intertemporal planner problem as

$$\max_{\{z_t, Q_{t+1}\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \beta^t \left(\log Q_t + \log\left((1-\alpha)\alpha^{-\frac{1}{1-\alpha}}L - z_t/\psi\right)\right), \tag{13}$$

subject to $Q_{t+1} = Q_t(1 + z_t(\gamma - 1))$.[32] The solution to this problem is consistent with a constant long-run growth rate where the rate of creative destruction can be shown, using straightforward manipulation of the first-order conditions, to be given by

$$z^{\star}_{SP} = \frac{(\gamma-1)\beta\psi(1-\alpha)\alpha^{-\frac{1}{1-\alpha}}L - 1 + \beta}{\gamma - 1}. \tag{14}$$

Contrasting the decentralized equilibrium with the planner's solution. There are three differences between the decentralized rate of creative destruction (10) and the planner solution (14), which partially go in opposing directions. As a consequence, the decentralized rate of creative destruction can in general be either too high or too low. The differences in the rate of creative destruction are:

1. The first term in the numerator is premultiplied by $\gamma - 1$ in the planner's solution, as opposed to just γ in the decentralized equilibrium. Underlying this discrepancy is the so-called "business stealing" effect. The planner internalizes only the incremental quality gain of each innovation relative to its starting level. In contrast, in the decentralized equilibrium, an innovating firm's incentive is governed by the potential profit it will make. As a successful innovator takes over the entire product

on their own products too.

[32] To ensure an interior solution with positive growth, we assume that the following parameter conditions hold: $(\gamma-1)\psi(1-\alpha)\alpha^{-\frac{1}{1-\alpha}}L > 1/\beta - 1$ and $(\gamma-1)\beta\psi(1-\alpha)\alpha^{-\frac{1}{1-\alpha}}L - 1 + \beta < \gamma - 1$.

market and therefore reaps the full benefit of the new quality level, it does not internalize that part of the profits are just stolen from a competitor.

2. There is an additional additive β term in the denominator in the decentralized equilibrium expression of $z^\star$, which pushes the rate of creative destruction down compared to the planner's solution. As subsequent innovations build on each other, the planner sees innovations as lasting forever and fully internalizes this knowledge spillover. In contrast, private firms only internalize the effect as long as they stay in business, a length of time that is uncertain given that they face creative destruction.[33] The higher β, the stronger is this discrepancy between the planning allocation and the decentralized allocation, as more weight is placed on the future.

3. The planner's solution has an additional multiplicative $\alpha^{-\frac{1}{1-\alpha}}$ term in the numerator. This difference arises because monopolistically competitive firms charge "too high" prices, leading to under-usage of intermediate inputs.[34] This misallocation of resources implies that the decentralized output level is too low, and as these type of models feature a scale effect, it spills over and pushes the decentralized growth rate down compared to the social optimal growth rate.

Discrepancy (1) above is novel and unique to endogenous growth theories that feature creative destruction, whereas (3) is a common feature of innovation-led growth models (see, e.g., Romer (1990)). Discrepancy (2) may show up in a similar form in endogenous growth models without creative destruction that feature a knowledge externality. In particular, discrepancy (1) opens up the possibility that the decentralized growth rate is too high compared to the social optimal growth rate. Unlike alternative macroeconomic models of growth, Aghion and Howitt's (1992) framework explicitly captures the conflicting interests inherent in the process of technological change. Growth is not like the tide that lifts all boats, but rather it generates (absolute) losers. As a consequence, the growth paradigm created by Aghion and Howitt brings distributional and possibly negative consequences of growth to light. More growth and technological progress does not always have to increase welfare but may in fact imply more suffering (for some). A striking way to see this is the theoretical possibility that the decentralized growth rate can be too high due to the business stealing effect. But not only the rents of business owners are destroyed through the process of creative destruction—the theory also predicts that the growth process goes hand in hand with more entry, exit, and churning in the labor market, as documented in Section 3.1.

Another novel aspect of Aghion and Howitt's (1992) model is the possibility of the case of "non-drastic" or "incremental" innovations. This case emerges when $\gamma < \left(\frac{1}{\alpha}\right)^{\frac{\alpha}{1-\alpha}}$ and the leading firm cannot sell at the markup factor $1/\alpha$. If the leading firm was charging a markup of $1/\alpha$, the eclipsed second-best quality producer could compete with the leader and make positive profits. Hence, under Bertrand competition, the maximum markup the leading firm can charge—in the case of non-drastic innovations—is $\gamma^{\frac{1-\alpha}{\alpha}}$. This connects the markup a firm can charge to its quality step size in the innovation process. Klette and Ko-

[33] This difference arises precisely because expected future profits are discounted more in the light of creative destruction, i.e., $z^\star$ shows up in the denominator of (4).

[34] The planner uses precisely $\alpha^{-\frac{1}{1-\alpha}}$ times as much of each intermediate input as in the decentralized equilibrium. Note that the planner's quantities are strictly larger than in decentralized equilibrium, as $\alpha^{-\frac{1}{1-\alpha}} > 1$ is fulfilled by the parameter restriction $\alpha \in (0, 1)$.

rtum (2004) built on this case and a flood of literature followed. In models with step-size heterogeneity across firms, or in models where the innovation step size is a choice variable, such settings of non-drastic innovations generate variable markups across firms.

3.4 Next theoretical steps and applications of the basic framework

The building blocks underlying the simple model above have proven to have far-reaching theoretical implications while still remaining tractable. As a result, the basic mechanism introduced by Aghion and Howitt (1992) has been further developed and successfully applied to a variety of questions in follow-up research by the laureates themselves and many others. Here we discuss such important next theoretical steps.

Market structure. The baseline model above is embedded in a monopolistic competition setting and does not feature strategic interactions across firms. Important efforts therefore aimed to generalize the framework in this respect, to capture richer interactions between innovation and competition. This crucial step was undertaken in Aghion et al. (1997, 2001). As in the basic model above, there is still a unit interval of product markets but within each product market, two firms are producing imperfect substitutes and compete à la Bertrand (or Cournot). With imperfect substitutes and oligopolistic competition, both firms will stay in the market and produce. A firm with a productivity edge over its competitor will, however, produce more and can charge a higher markup. Justified by some tacit knowledge in R&D, innovations of the two firms are then assumed to take place step by step as opposed to by leapfrogging. This means that each firm climbs its own productivity ladder; i.e., a firm that is lagging behind has to catch up rung-by-rung and cannot directly overtake the leading firm by building on its rival's productivity. This framework results in very rich interactions between competition and innovation. On the one hand, the productivity gap between the two firms crucially determines markups and the incentive to invest in R&D. On the other hand, the equilibrium distribution of productivity gaps across product markets depends on the innovation incentives and the implied R&D activity of the two firms.

Using such a framework, Aghion et al. (2001) studied how changes in the substitutability of products affect the innovation incentive and in turn aggregate growth. A higher substitutablility of the products implies a higher level of competition and generally lower level of profits. However, it also changes the steepness of the firm's value function in the productivity gap and therefore its incentive to innovate. When the two firms have the same productivity, i.e., are neck-to-neck, then the higher the elasticity of substitution, the higher the incentive to invest in R&D in order to become a leader. This is the so-called escape competition effect: neck-to-neck firms have a particularly high incentive to innovate if the product market competition is fierce. In contrast, for firms clearly lagging behind their competitors, the so-called Schumpeterian effect kicks in. In particular, for such a lagging firm, the steep section of the value function (at the point when it may overtake the leading firm) is far in the future. As a consequence, given sufficient time discounting, lagging firms are discouraged to innovate, and it can be shown that a laggard's innovation incentive falls in the substitutablility of the products. Finally, as the long-run equilibrium distribution of productivity gaps is endogenous and the innovation incentive differs between markets that are neck-to-neck and markets with a productivity gap, there is also a compositional effect. This type of step-by-step innovation setup can generate the prediction of a non-monotonic relationship between product market competition and innovation. This framework has been widely applied in the follow-up literature to study the interplay between innovation, patent protection, and competition (see Aghion et al. (2001), Aghion et al. (2005), Acemoglu and Akcigit (2012), and Akcigit and Ates (2023) to name a few).

Technological waves. The innovations studied in the baseline framework are what Mokyr describes as micro inventions. Follow-up work extended the theory by Aghion and Howitt to study macro inventions or general purpose technologies as described by Bresnahan and Trajtenberg (1995). Such versions of the theory can be used to study technological waves and their effect on inequality (see Helpman and Trajtenberg (1994) and Aghion et al. (2002)).

Firm heterogeneity. The basic creative destruction mechanism in the baseline model generates significant firm heterogeneity. The model features conflicting interests, entry and exit of firms, and a product lifecycle of stochastic length. A general theme of the subsequent literature was to add more heterogeneity in terms of competition (as discussed above) or in terms of R&D technology. In the basic framework of Section 3.3, for simplicity, the innovation technology is assumed to feature constant returns to scale. In contrast, Aghion and Howitt (1992) and a large body of follow-up literature entertain convex innovation costs, which will pin down the equilibrium R&D effort of each individual entrepreneur or firm. Such a setting has often been augmented with heterogeneity in R&D costs or in the innovation step sizes (see, e.g., Luttmer (2011), Akcigit and Kerr (2018), Acemoglu et al. (2018), and Aghion et al. (2023)). Combined with richer market structures (as discussed above), this kind of addition allows us to study the interplay between incumbents and entrants, old and young, small and large, and growing and shrinking firms, all in a market economy with conflicting interests.

Innovations by incumbents. Because of the Arrow replacement effect, in the basic model of the previous section, all innovations are carried out by new entrants. In reality, however, large incumbent firms do systematically improve on their products over time, and the literature has come up with various ways of adding such incumbent own-innovation to the basic framework. The step-by-step innovation framework of Aghion et al. (2001) features incumbent firms improving their own products. Klette and Kortum (2004) added multi-product firms, which innovate to expand into new product markets. In Akcigit and Kerr (2018), firms can increase sales by improving their own products and do so as a result of convex R&D cost with low initial marginal cost of innovation. As modified by Peters (2020), firms have incentives to improve on their own products, as this allows them to increase the markup on their products (therefore boosting their profits).

Firm dynamics. In models of firm heterogeneity, size distribution and firm dynamics are generated by different firm-level productivities and changes therein (see Jovanovic (1982), Hopenhayn (1992), Melitz

(2003)). In the data, we observe firms that downsize (and exit) very rapidly, suggesting that some firms must have been hit by large negative shocks. Creative destruction theory offers a very powerful and persuasive explanation: firms that see their product markets eclipsed by an innovation of a competitor rapidly lose business and might even be forced to exit.[35] The building block pioneered by Aghion and Howitt therefore found a powerful application in models of firm dynamics. This extended the pioneering work on firm heterogeneity carried out by others by providing deeper explanations for the idiosyncratic productivity changes that drive firm dynamics in those models. Furthermore, such application of the framework by Aghion and Howitt allows for predictions of the long-run firm size distribution, market concentration, and market power. Klette and Kortum's (2004) paper was key in making this connection, and many others, such as Lentz and Mortensen (2008), followed suit. This line of research has sparked further activity that continues to grow, where the aims are more quantitative—i.e., trying to match not only qualitative features of the data but also their magnitudes—than in the earlier literature (see, e.g., Luttmer (2011), Atkeson and Burstein (2019), Akcigit and Kerr (2018), or Acemoglu et al. (2018)). This current research in the field also blends in other innovation mechanisms such as variety expansion (Romer, 1990) or the notion that ideas are harder and harder to find (Jones, 1995; Bloom et al., 2020); in all of this work, the element of creative destruction remains central in matching the observed firm dynamics.[36]

3.5 Empirical follow-up studies

The emergence of the theory of creative destruction stimulated applied research in the field, greatly expanding the literature testing the theory's predictions in the data. This endeavor relied heavily on microeconomic industry-, firm-, plant- and product-level data. The creative destruction paradigm features significant asymmetric effects across firms within markets (entry vs. exit, expansion vs. downsizing), which cannot be tested in aggregate data. Thus, to confront the theory, and its most important predictions, with data would have to involve microeconomic detail. More generally, as growth rates of advanced economies were remarkably stable over time, one has to rely on more disaggregated data to test and discipline growth theories quantitatively.

The theoretical advances in the area of creative destruction also fell on fertile ground: large administrative datasets on firms, patents (see Griliches (1998) and Hall et al. (2001)), and products became more and more readily available, and these data could be linked to, e.g., background information on inventors and entrepreneurs (Bell et al. (2019) and Aghion et al. (2017)). In the following, we briefly mention some of these empirical follow-up studies that demonstrated both the empirical validity and relevance of the creative destruction paradigm.

The relationship between competition and innovation. Models of endogenous growth that do not feature creative destruction predict growth and product market competition to be negatively related to each other: big upfront R&D investments must be incentivized by high markups. The step-by-step innovation

[35] Furthermore, as the arrival rate of successful innovations is stochastic in models of creative destruction, the mechanism naturally implies that there are shocks to productivity/profitability on the firm level.

[36] See, e.g., Peters and Walsh (2021) for an example of such a general structure which adds variety expansion and semi-endogenous growth elements.

models developed by Aghion et al. (1997, 2001) can break this strong theoretical prediction that is typically not borne out in the data: Nickell (1996), Blundell et al. (1995), and Blundell et al. (1999) provide empirical evidence pointing rather to a positive relationship between innovation and product market competition. Aghion et al. (2005) document an inverse U relationship between competition and innovation and show how the theory can generate such a pattern.[37] More competition may foster growth in frontier firms but discourages it in non-frontier firms. At the same time, competition decreases the fraction of markets with neck-to-neck firms, implying—through a compositional effect—that innovations eventually fall in the level of competition. Aghion et al. (2005) also show empirical support for these auxiliary predictions.

Firm dynamics. A large applied literature investigated the relentless process of entry, exit, expansion, and downscaling of firms and its connection to economic growth. Davis and Haltiwanger (1992) and Davis et al. (1996) document a large rate of job creation and destruction in the U.S. economy within narrowly defined industries (in part illustrated in Section 3.1), and Haltiwanger et al. (2013) and Hsieh and Klenow (2014) show how firms grow over their lifecycle conditional on survival. These patterns can be replicated by the type of model by Klette and Kortum. Empirical moments of firm dynamism were successfully used to discipline and quantify endogenous growth theories that feature creative destruction. A key question this literature addresses is how much entrant vs. incumbent, large vs. small, and young vs. old firms, or different type of innovations, contribute to aggregate output growth (see Foster et al. (2001), Lentz and Mortensen (2008), Bartelsman and Doms (2000), Luttmer (2011), Akcigit and Kerr (2018), Atkeson and Burstein (2019), and Garcia-Macia et al. (2019)).

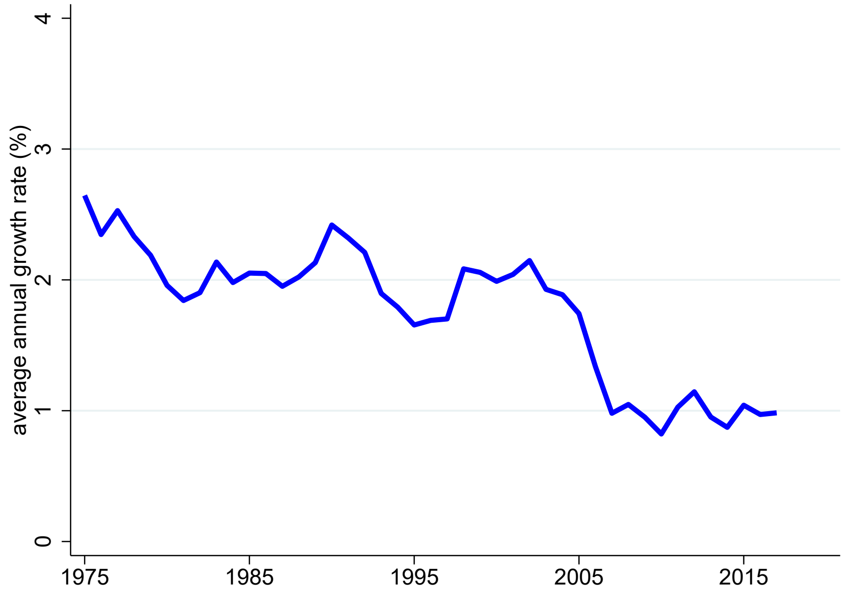
Recent macroeconomic trends. Productivity growth rates in advanced economies remained remarkably stable over time for most of the post World War II period. However, since the 2000s, OECD countries have witnessed a significant slowdown of productivity growth (Figure 11 illustrates labor productivity). The same period was characterized by a fall in labor's share of total income, and additional evidence points to rising markups (see Akcigit and Ates (2021) for a summary). Absent a mechanism of creative destruction, it is typically not possible to square these observations. Over recent years, many of the advanced economies also saw falling firm entry and exit rates and declining job reallocation rates, which is corroborating evidence that the productivity slowdown was indeed accompanied by a reduction in creative destruction (for the U.S. see Figure 8 and the evidence in Decker et al. (2014)). Recent quantitative work investigates the reasons behind the productivity growth slowdown through the lens of an innovation-led growth model in the spirit of Aghion and Howitt (see, e.g., Aghion et al. (2023), Akcigit and Ates (2023), and De Ridder (2024)).

3.6 Policy relevance

The creative destruction paradigm has direct policy implications. At its core, there is the prediction of a rich interplay—with a possible non-monotonic relationship—between competition and innovation. Un-

[37] The empirical finding is confirmed when instrumenting competition with (exogenous) policy changes.

Figure 11: Labor productivity growth in OECD countries



Source: Penn World Table 10.01. Five-year centered moving average of the yearly labor productivity growth rate across OECD countries. Averages across countries are weighted by real GDP. This is an updated version of figure 10.2 from Boppart and Li (2023).

der cut-throat competition, firms find it hard to recover R&D through future profits and growth will be low. At the other end of the spectrum, uncontested monopolists typically have low incentive to innovate too. Generally, entrenched incumbents will have a tendency to block entry and hinder growth possibly with the help of government policies. Below, we briefly mention policy aspects that tightly tie in with the theoretical concept of creative destruction introduced by Aghion and Howitt.

Competition and innovation policy. An important message is the fact that the creative destruction paradigm can generate a non-monotonic relationship between competition and innovation. The message that innovation and competition policies are inherently linked, and that they cannot be studied in isolation, is deeply engrained in today's antitrust policies or in considerations of R&D subsidies (see, e.g., Furman et al. (2019), Stigler Committee on Digital Platforms (2019), Nadler and Cicilline (2020), or Crémer et al. (2019)). The element of creative destruction is also indispensable for the analysis of optimal patent policy (Acemoglu and Akcigit (2012)).

Suboptimal R&D investments. A natural question is whether the decentralized growth rate is too high or too low, as the latter possibility can arise in models of creative destruction due to the business stealing effect. At the aggregate level, the available evidence clearly points to growth being too low compared to the social optimum (see Jones and Williams (1998), Jones and Williams (2000) and Atkeson and Burstein

(2019)). This, however, is still consistent with some industries or firms spending too much on R&D precisely because of the business stealing effect (see, e.g., Aghion et al. (2022)). This suggests that one-size-fits-all R&D subsidies are suboptimal.

Winners, losers, and social insurance. To attain an economy's full growth potential, production factors have to continuously flow to their most productive use. The creative destruction paradigm suggests that higher growth goes hand in hand with increased business dynamism. What societal conflicts arise as a result of this dynamism? As pointed out above, the baseline model of creative destruction features a representative consumer, so that although firms are in conflict between each other, what matters for people's welfare is just aggregate consumption. This is of course a drastic simplification: in reality, different consumer and worker groups are influenced by competition and income is shifted between them. The literature has studied such conflicts of interest as well.

A specific focus has been placed on the labor market. In particular, as a consequence of increased dynamism, the job separation rate is elevated in high-growth periods and industries. In a frictional labor market, this may result in a higher unemployment rate (Aghion and Howitt (1994)). Hence, there is a role for policy to insure unemployed workers who have seen their jobs being creatively destroyed by competitors, and to retrain them so that they find new employment in expanding firms and industries. Such a social insurance system is reminiscent of the "flexicurity" system as introduced by Denmark and the Netherlands in the 1990s. The social welfare state may also be important to secure broad support in society for policies that lead to growth but also unchain the forces of creative destruction. Aghion et al. (2016) show empirical evidence that—after controlling for the unemployment rate—the rate of creative destruction (as measured by job turnover) correlates positively with subjective well-being across different metropolitan statistical areas of the U.S. Furthermore, Aghion et al. (2016) show that the more generous the unemployment benefits, the less negatively associated the rate of job destruction is with subjective well-being.

Tapping into the entire pool of talents. The creative destruction model suggests that the actions of inventors and entrepreneurs are crucial and ultimately determine the long-run growth rate of an economy. As a consequence, human capital and the selection of who becomes an inventor have far-reaching consequences. It is important not to restrict the pool of potential entrants and to make sure that the available entrepreneurs direct their activity to the most productive use (see Baumol (1996) and Aghion and Howitt (1996)). As Aghion et al. (2019) show, measures of social mobility are indeed positively related to growth across U.S. commuting zones. At the same time, high top income inequality—if based on innovation rents—may have to be tolerated in order to incentivize entrepreneurs and inventors to undertake their innovative activities (see Jones and Kim (2018) and Aghion et al. (2019)). In this sense (static) income inequality and social mobility may both stimulate innovations and growth.

4 Conclusions and implications for society

Over the past 250 years, the world has seen more economic growth than ever before in human history. The driving force behind this process is technological change. This year's laureates explain the period of sustained economic growth through the same paradigm: growth fueled by the forces of innovation, disruptive on the microeconomic level but still consistent with sustained aggregate growth. The laureates studied this process of creative destruction and of the feedback between science and applied technology in detail and show how it allows us to escape the fate of diminishing returns, and leads to sustained economic growth.

The literature points to looming threats on the horizon regarding future technological change. Furthermore, measured productivity growth has already slowed down somewhat over the past decades. Some scholars argue that the world has already seen history's greatest innovations and is doomed to a future of stagnation (e.g., Gordon (2017)). Yet others warn about the disruptive effects from ongoing digitization and automation on the future of work (e.g., Frey and Osborne (2017)), or the erosion of democratic values (e.g., Johnson and Acemoglu (2023)). In addition, major concerns relate to the environmental transition and how to square economic growth with the physical boundaries coming from finite natural resources. Sustained growth is clearly not equal to sustainable growth, as the negative externalities from increased production pose serious strains on our planet. With a science and technology-focused view, however, social and environmental challenges should set into motion searches for novel techniques to address them, so that the technological process itself may be interpreted as a self-correcting process (Mokyr, 2018b, p. 21). Naturally, the time lags and losses involved in such a process might be substantial, giving rise to negative attitudes towards the process of technological change, or what popularly may be regarded as mostly "destructive creation."

A positive upshot is that advancing technologies, such as artificial intelligence (AI), bring a new era of data science that could impact overall science much beyond large-scale calculations and standard statistical analysis. Mokyr's work highlights that technologies holding the potential to enlarge the propositional knowledge base, and simultaneously decrease the costs for practitioners to access available knowledge, may improve the feedback loops between propositional and prescriptive knowledge. Equipped with more powerful tools, our understanding of natural processes may accelerate and new applications, some imaginable and some not, will continue to appear.

The work by Aghion and Howitt provides us with the theoretical framework to systematically think about the key determinants of the long-run rate of technological change. One such determinant is the competitive environment. An argument, fundamentally based on Aghion and Howitt's work is that increased firm concentration and market power may be an important factor behind the more recent negative productivity trends. This argument, furthermore, suggests that regulatory oversight is an important part of a policy mix going forward. Relatedly, the nature of technological change in motion right now—driven in large part by AI—is likely to lead to significant structural adjustments and many "losers", at least in the short run. Supporting those who need help in changing jobs or occupation while not hindering the transition is an important challenge for policymakers.

Taken together, the work of this year's laureates help us understand the forces underlying sustained economic growth. Economic stagnation, not growth, has been the norm in human history, and the role of science, innovation, and creative destruction cannot be overstated in the unpredecedented economic growth experience since the Industrial Revolution. Thus, while knowledge is currently expanding at a fast rate, societies need to pay attention to potential suppression of pluralism, rising market power, and the risk that established interest groups will block the forces of creative destruction with an adverse effect on economic growth.

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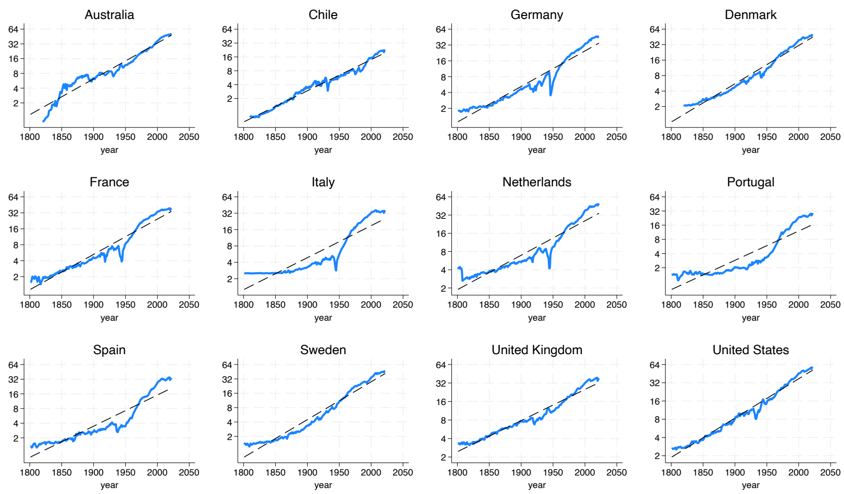
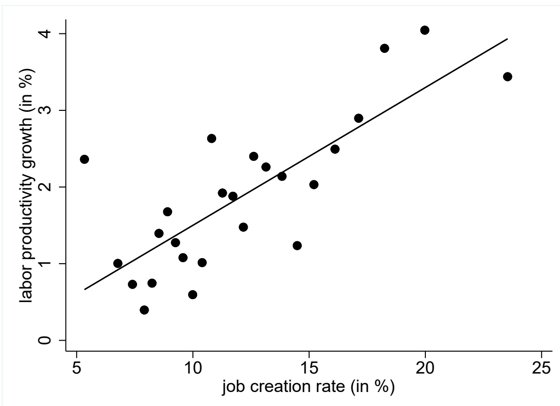
Appendix

Figure A1: Real GDP per capita in the advanced economies

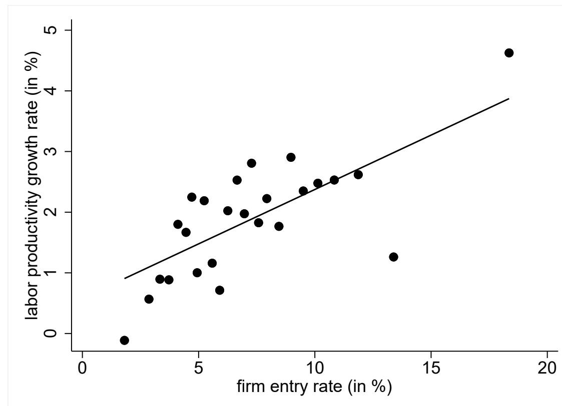


Data source: Maddison database. GDP per capita in thousands of USD in 2011 prices.

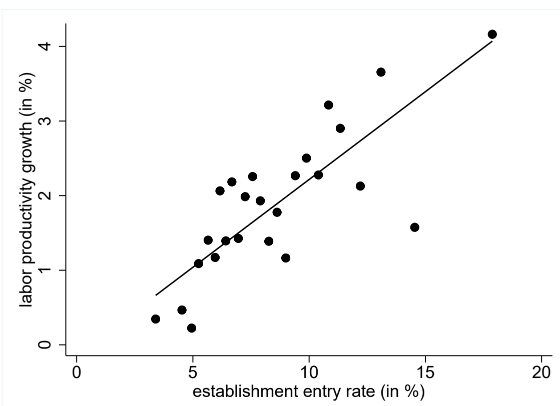
Figure A2: Labor productivity growth vs. measures of dynamism, 1988–2022



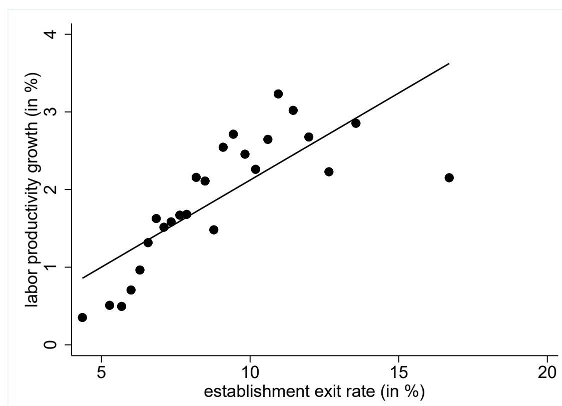
(a) Job creation rate



(b) Firm entry rate



(c) Establishment entry rate



(d) Establishment exit rate

The figures show binned-scatter plots of 5-year averages by industry in firm exit rates, or job destruction rates vs. the 5-year averages of labor productivity growth rates. The sample consists of 159 four-digit industries and 7 five-year periods. *Data source:* Business Dynamics Statistics for dynamism variables and BLS for labor productivity growth.