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THE SCIENTIFIC REVOLUTION AND ITS ROLE IN THE TRANSITION TO SUSTAINED ECONOMIC GROWTH

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Abstract

We propose a Unified Growth model that analyzes the role of the Scientific Revolution in the takeoff to sustained modern economic growth. Basic scientific knowledge is a necessary input in the production of applied knowledge, which, in turn, fuels productivity growth and leads to rising incomes. Eventually, rising incomes instigate a fertility transition and a takeoff of educational investments and human capital accumulation. In regions where scientific inquiry is severely constrained (for religious reasons or because of oppressive rulers), the takeoff to modern growth is delayed or might not occur at all. The novel mechanism that we propose for the latent transition towards the takeoff could contribute to our understanding of why sustained growth emerged first in Europe.

JEL classification: O11, O31, O33, O41.
Keywords: Scientific Revolution, Industrial Revolution, Basic Science, Applied Science, Takeoff to Sustained Growth, Unified Growth Theory.

Though the world does not change with a change of paradigm, the scientist afterward works in a different world.
(Thomas S. Kuhn, 1970)

1 Introduction

Much has been written about causes of the Industrial Revolution, Europe's little divergence and the great divergence between Europe and the rest of the world in the 19th century. Although it is widely accepted that the explanation for Britain's success must come from understanding the development and improvement of new technologies, researchers differ on the reasons why Britain and Europe were more successful than others. Central in this debate is the disputed role of science. Strong support for an early significant impact of science comes from Jacob (2014). She pleads to focus on the complexities of science-based technological change. Or more precisely, on those inventions that could not have been developed without knowledge of Isaac Newton's laws of motion, the law of universal gravitation, and the subsequent research on vacuums in the 17th century (see also Rosen, 2010).[1] Moreover, Mokyr (2002) stresses that the Enlightenment had a dual impact on the first Industrial Revolution both because it was conducive to the production of more useful knowledge, while at the same time reducing access costs by improving incentive structures and promoting better economic policy and institutions. For example, the "Republic of Letters", a group of scientists and intellectuals who discussed and shared ideas intensively, changed the way of knowledge dissemination and finally led to the establishment of the first journals (Mokyr, 2016).

Critics of a causal relationship mainly refer to the textile sector, where nearly all important innovations such as the spinning jenny, the waterframe, and the moule were invented by rather uneducated inventors with high creativity who developed the machines through a learning-by-doing process in a relatively isolated scientific environment. Mokyr suggests that despite some important inventions only generating a one-shot increase in productivity that did not translate into sustained growth, applied knowledge increased nonetheless, which allowed continuous inventions to follow (see Allen, 2011). Although Allen sees the role of

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[1] The debate already flourished in the 1960s and centered around Musson and Robinson (1989), who pointed out that the inventions of the Industrial Revolution need more than just "unlettered empiricism" (Ó Gráda, 2016, 225).

relative factor prices as most important for the success of British innovations, he agrees with Mokyr that the inventions of the Industrial Revolution have led to processes that changed the economy sustainably and made further technological developments possible. Even though numerous differing opinions on the actual impact of science on the early industrial take-off exist, there seems to be a general agreement that scientific knowledge accumulated over time and was most important for sustained economic growth from the 1850s onward. This is also supported by recent research of Cinnirella and Streb (2017). They have shown for Prussia that the second Industrial Revolution can be seen as the transition period for the role of human capital. Whereas in the first Industrial Revolution, useful knowledge of a small group of educated inventors was related to innovation and growth, in the subsequent twentieth century, the quality of basic education was important for worker's productivity and R&D processes.

The Unified Growth Theory as developed in the seminal works of Galor and Weil (2000) and Galor (2005, 2011)[2] led to a better understanding among economists on the mechanisms that triggered the escape from the Malthusian trap, resulting in the Industrial Revolution and in the takeoff toward sustained modern economic growth. This strand of literature usually emphasizes the quality-quantity tradeoff that affects the size and the education of the labor force and, with it, the rate at which new ideas are developed. What these models do not consider is the above explained scientific basis that is necessary for productive applied R&D to take place. Prettner and Werner (2016) include a basic scientific research sector in an R&D-based growth framework along the lines of Romer (1990) and Jones (1995)[3] and analyze the extent to which basic research influences modern economic growth. However, Prettner and Werner (2016) do not focus on the interactions between basic scientific research and applied research over the very long run and how these interactions facilitate a takeoff toward the phase of sustained economic growth.

We aim at contributing to the literature by analyzing the extent to which the Scientific Revolution could have influenced the following escape from Malthusian

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[2] Other prominent contributions include the works of Jones (2001), Kögel and Prskawetz (2001), Hansen and Prescott (2002), Galor and Moav (2002, 2004, 2006), Doepke (2004), Cervellati and Sunde (2005, 2011), Strulik and Weisdorf (2008), Galor et al. (2009), and Strulik et al. (2013).

[3] For a non-exhaustive list of contributions in endogenous, semi-endogenous, and Schumpeterian growth theory, see, for example, Grossman and Helpman (1991), Kortum (1997), Dinopoulos and Thompson (1998), Peretto (1998), Segerström (1998), Young (1998), Howitt (1999), Dalgaard and Kreiner (2001), Strulik (2005), Bucci (2008), Peretto and Saeter (2013), Strulik et al. (2013), and Prettner (2014).

stagnation. We do this by merging the two strands of Unified Growth Theory and R&D-based endogenous growth theory with both basic scientific knowledge and applied patentable knowledge. As is standard in the Unified Growth literature, the model features utility-maximizing households with a quality-quantity tradeoff regarding the number of children and the children's education. An increase in income over time leads the economy up to a point at which investments in education become positive and a fertility transition sets in (see, for example, Strulik et al., 2013). The associated increase in human capital accumulation is then one of the central divers of the takeoff toward sustained economic growth.

In contrast to the standard Unified Growth literature, however, there is an additional engine for the takeoff toward sustained economic growth, which provides the basis for the rise in the income level that leads to the fertility transition in the first place. This second driving force is represented by the evolution of the stock of basic scientific knowledge, which is a necessary input in the production of applied knowledge in a purposeful applied R&D sector (Romer, 1990; Jones, 1995). Applied R&D only becomes profitable and operative once large enough stocks of basic scientific knowledge and human capital in a society exist. Only then does the applied research sector start to produce the patents that are needed in the intermediate goods sector to produce the differentiated machines that are, in turn, required in the final goods sector to produce the consumption aggregate. The more basic scientific knowledge exists, the more productive is applied R&D and the earlier the takeoff to sustained growth can occur.

The structure of our model makes clear that the takeoff of applied R&D is a central driver of long-run economic development that enables the fertility transition later on. To avoid inconsistencies, we abstract from technological advancements during the early phase of the Industrial Revolution. The reason is that implementing an additional R&D sector that solely builds up on the existing stock of applied knowledge and disregards science would complicate the model substantially, while providing little insights on the role of science and human capital for the economic takeoff.

Overall, our approach fits the historical evidence that over time British endowment of science-based knowledge was growing, but only during the second Industrial Revolution (1850s), when steam and coal occupied center stage, this basic knowledge mattered. The sustained takeoff in applied R&D, however, cannot occur if there is no basic scientific knowledge base in the economy. This mechanism is our proposed formal modeling of the contribution of the Scientific Revolution as a major trigger of the second Industrial Revolution and the takeoff to modern economic growth as described by Wootton (2015) and Mokyr (2016). We believe that the suggested novel approach enables a more sophisticated understanding of the growth process over the very long run and of the economic importance of the interaction between the basic scientific knowledge stock of a society and the accumulation of applied knowledge in the transition from stagnation to sustained long-run economic progress. As such, our framework may provide an explanation why Britain/Europe was first, if we assume that the speed of accumulation of as well as the proximity to scientific knowledge was determined by the Enlightenment.

The paper is organized as follows. In Section 2, we introduce the basic model assumptions, the structure of the household side, and the properties of the production side of the economy. In Section 3, we derive the balanced growth path analytically. In Section 4, we present the model simulation and discuss comparative statics with regards to the timing of the Scientific Revolution and its effect on the timing of the later Industrial Revolution. Finally, in Section 5, we summarize our findings and provide suggestions for future research.

2 The model

In this section, we describe the basic knowledge-driven growth framework in the vein of Romer (1990) and Jones (1995) into which we incorporate an endogenous fertility-education decision (Becker and Lewis, 1973; Galor and Weil, 2000; Strulik et al., 2013) and a basic science sector that deciphers the laws of nature and lays the foundations for applied knowledge creation (Prettner and Werner, 2016).

2.1 Basic assumptions

Consider a small open economy that is populated by three overlapping generations: children, adults, and retirees. Children receive consumption from their parents and retirees consume out of their savings accumulated in adulthood. At the end of old-age, individuals die with certainty.[4] We conceptualize adults as

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[4] For simplicity, we abstract from pension schemes and from a changing life expectancy because pension schemes are rather a 20th century development (Boersch-Supan and Wilke, 2004) and the implementation of endogenous life expectancy would complicate the model without altering the central results (for a Unified Growth Model that takes changing mortality into account, see Cervellati and Sunde, 2005).

single-sex parents[5] that make all economically relevant decisions on i) consumption during adulthood and old-age, ii) the number of their children, and iii) the education investments in each child. The resulting consumption-saving decision impacts on intermediate goods production and thereby on the incentives to develop new blueprints in applied R&D. A necessary input in applied R&D is a basic understanding of the laws of nature, of scientific inquiry, and of the way to disseminate new insights. This knowledge is generated in a basic scientific sector by thinkers who decipher how nature works. The better a society's understanding of the laws of nature, of scientific inquiry, and of knowledge dissemination is, the more productive is applied R&D. Since applied R&D is one of the main drivers of long-run economic growth, basic scientific knowledge acts as a catalyst of the takeoff to sustained economic growth.

The fertility decision of adults determines the evolution of the population size, whereas the education decision determines individual human capital accumulation. There is a quality-quantity tradeoff of parents in the sense that they can increase the number of their children but at the expense of lower investments in the education of each child (and vice versa). For low levels of economic development, education investments are a luxury good and parents find it optimal to choose the corner solution of no education and high fertility. Once income surpasses a certain threshold, investment in children's education becomes positive, which triggers a quality-quantity substitution of increasing education investments and falling fertility during the transition to the modern growth regime. As in standard Unified Growth models, this is another main engine for the takeoff to sustained economic growth.

2.2 Consumption side

Individuals derive utility from consumption during adulthood, c_t, from consumption during retirement, $c_{t+1} = s_t(1 + \bar{r})$, where s_t are savings and $\bar{r}$ is the rate of return, from having children, n_t, and from the education investments in their children, e_t.[6] For simplicity, we assume a small open economy such that the

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[5] The assumption of single-sex adults is made to abstract from modeling intra-family bargaining processes, which allows us to focus on the macroeconomic effects. For contributions that investigate the intra-household decision process in more detail see, for example, de la Croix and Vander Donckt (2010), Bloom et al. (2015), Prettner and Strulik (2017), and Doepke and Kindermann (2019).

[6] Following Strulik et al. (2013) we adopt this short-cut formulation in which children's education enters the utility function directly. This can be justified by a "warm glow" motive of giving (cf. Andreoni, 1989) and leads to similar tradeoffs as in the literature in which children's

capital rental rate is determined on the world market. Utility is logarithmic and determined according to the following function

$$u_t = \log(c_t) + \beta \log[s_t \cdot (1+\bar{r})] + \xi \log(n_t) + \theta \log(e_t + \bar{e}), \tag{1}$$

where β refers to individual impatience[7], ξ represents the preferences of parents for the number of children, and θ the preferences of parents for children's education. The parameter $\bar{e}$ represents a minimum informal education level that children acquire through observation and learning-by-doing even if parents do not invest in the education of their children at all (see Strulik et al., 2013). This parameter ensures that education is a luxury good and it does not pay off for poor societies to invest in formal education. Thus, our formulation captures the situation in agrarian pre-industrial societies—in which children mainly learned by working alongside their parents and peers on the fields—rather well.

The lifetime budget constraint is given by

$$(1-\psi n_t) w_t h_t = c_t + s_t + \eta e_t n_t, \tag{2}$$

where w_t is the wage rate per unit of human capital, h_t. The price of a unit of education is given by η, whereas ψ denotes the fraction of parental time that raising a child requires (Galor and Weil, 2000; Galor, 2005, 2011). The product $w_t h_t$ is labor income per worker for a given level of individual human capital and $1-\psi n_t$ represents the labor force participation rate. Individuals save s_t of their wage income for old-age consumption. The reminder is spent on consumption during adulthood, c_t, and on children's education, $\eta e_t n_t$. Expenditures on education depend, in turn, on the cost of each unit of education, η, the quantity of education, e_t, and the number of children, n_t. Overall, this setting implies a quality-quantity tradeoff: on the one hand, more children increase utility; on the other hand, more children decrease the amount of resources that can be devoted to the education of each child.[8]

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human capital or children's income appear in the parental utility function instead of children's education. However, the analytical solution can be much easier obtained with the short-cut formulation.

[7] The parameter β induces a similar individual behavior as a probability to die between adulthood and old age. Thus, a small β can also be interpreted as having a relatively short retirement phase, which fits well to most of human history (Chakraborty, 2004; Baldanzi et al., 2019b).

[8] If, instead, the costs of fertility were given by a fixed amount of resources, fertility would increase perpetually with rising income, which is counterfactual. Since, in this case, education also rises with income, the quality-quantity tradeoff that is established theoretically and

Maximizing (1) subject to (2) yields the following optimality conditions for consumption, savings, fertility, and education

$$\begin{aligned} c_t &= \frac{w_t h_t}{1+\beta+\xi}, \qquad n_t = \frac{(\xi-\theta)h_t w_t}{(1+\beta+\xi)(\psi h_t w_t - \eta\bar{e})}, \\ e_t &= \frac{\theta\psi h_t w_t - \xi\eta\bar{e}}{\eta(\xi-\theta)}, \qquad s_t = \frac{\beta w_t h_t}{1+\beta+\xi}. \end{aligned}$$

As is intuitive, consumption and savings increase with income, while consumption decreases with the discount factor and savings increase with the discount factor. In addition, we observe that fertility stays constant in the long-run limit even for rising income, which is in line with the literature (Galor and Weil, 2000; Galor, 2005, 2011; Strulik et al., 2013). For fertility to be positive, $\xi > \theta$ and $h_t w_t > \eta\bar{e}/\psi$ have to hold. These parameter restrictions are reasonable because they rule out the situation in which parents would want to invest in the education of their children before choosing to have children at all. In addition, the parameter restrictions ensure a minimum level of income that is needed for positive fertility (i.e., to prevent the population from becoming extinct in the next generation). Education investments cannot be negative such that the possibility of a corner solution emerges for low income levels as follows:

$$e_t = \begin{cases} 0 & \text{for } w_t h_t < \xi\eta\bar{e}/\theta\psi \\ \frac{\theta\psi h_t w_t - \xi\eta\bar{e}}{\eta(\xi-\theta)} & \text{otherwise.} \end{cases}$$

Altogether, parents only invest in the education of their children after wage income has surpassed the threshold $\xi\eta\bar{e}/\theta\psi$.

2.3 Human capital

Children's education determines the next generation's level of human capital when the children of the previous period become adults and supply their time on the labor market. To derive adult's human capital, we set the parental expenditures on education equal to the costs of education (the salaries of teachers) and isolate the implied employment level of teaching personnel. Aggregate educational expenditures of parents are given by $\eta e_t n_t L_t$, where L_t is the number of workers/households in period t. Thus, aggregate educational expenditures amount to education expenditures per child $(\eta \cdot e_t)$, multiplied by the number of

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empirically (Li and Zhang, 2007; Galor, 2011; Fernihough, 2017) would vanish.

children (n_t), and aggregated over all households that invest in education (L_t). The costs of education are the wages of teachers given by $H_t^E w_t$, with H_t^E being the aggregate human capital employed in education. Equating educational expenditures with educational costs and solving for human capital employment in the schooling sector yields

$$H_t^E = \frac{\eta e_t n_t L_t}{w_t}.$$

Assuming that the human capital of the next generation depends on the educational resources invested in each child and denoting the productivity of teachers by μ, individual human capital at time $t+1$ pins down to

$$h_{t+1} = \frac{\mu H_t^E}{L_{t+1}} + \bar{e}.$$

In this expression, μH_t^E refers to the provision of economy-wide schooling. Dividing economy-wide schooling by the number of pupils in period t (i.e., the number of adults in period $t+1$), yields educational resources devoted to each child, which represents the quality of schooling. In case of a poor economy with a low income level, education expenditures are zero and no teachers are employed in the economy. Pupils would then solely learn by observing their parents and peers such that individual human capital stayed equal to the costless informal education that each child obtains, $\bar{e}$. This is the situation in the era of the Malthusian stagnation.

2.4 Production side

Apart from education, there are four sectors, the final goods sector, the intermediate goods sector, the applied R&D sector, and the basic scientific research sector. The aggregate final good is produced under perfect competition using workers and an intermediate good as inputs. The intermediate good, in turn, is produced under Dixit and Stiglitz (1977) monopolistic competition using one unit of final output to produce one unit of the intermediate good, x_t (cf. Aghion and Howitt, 2009). For the monopolist to produce the intermediate good, a blueprint needs to be bought from the applied research sector. The necessary funds are collected by issuing shares that can be purchased using household's savings. For simplicity, we abstract from physical capital in the production process. Its inclusion would not alter our main findings but it would complicate the model substantially (see also Galor and Weil, 2000).

The accumulation of applied knowledge (in the form of patents/blueprints) follows Romer (1990) and Jones (1995) after the takeoff to modern economic growth occurred. Applied knowledge is produced in a purposeful R&D sector in which profit-driven intermediate goods producers invest in the creation of the new patents/blueprints to derive a stream of profits via the associated monopolistic competition with other firms. We augment this setting by a basic science sector that deciphers the laws of nature and invents the methods of scientific inquiry. The stock of accumulated knowledge in this sector provides the basis for applied research. Since the laws of nature and the way of performing science cannot be patented, the output of this sector is non-excludable and this sector is not profit-driven. The ideas that are generated in this sector are non-rival such that their use by one scientist in applied research does not impinge on the productivity of the idea when other applied scientists use them.

We conceptualize the non-excludability of the results of scientific inquiry in the sense that great minds are either i) intrinsically motivated to think about how nature works or ii) that they do it because it raises a thinker's reputation among her peers. In modern times, basic research is typically funded by governments and conducted in research institutes and universities.[9] Since we do not want to overburden our model, we abstract from the public financing of modern basic science and focus on the potential way how basic scientific discoveries could historically have occurred and contributed to the takeoff to modern knowledge-based economic growth. The underlying assumption is that the number of eureka moments increases with the size of the population (Kremer, 1993) and with its education level (Strulik et al., 2013). Scientists might also form societies/journals to disseminate their thoughts and ideas such that the knowledge they create diffuses to other parts of society and can be used by the scientists in the applied research sector to create new patents/blueprints (Mokyr, 2002, 2005, 2016; Wootton, 2015). More generally, the output that this sector produces could be thought to comprise everything that makes it easier to discover new technologies and accumulate more basic and applied knowledge. In that sense, the output of the basic scientific sector can be interpreted as an important part of the *Culture of Growth* (Mokyr, 2016) that is necessary for a society to engage in the creation of new ideas and thereby to foster *progress* (Wootton,

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[9] For the modeling of a modern basic research sector along these lines, see, for example, Gersbach et al. (2012), Gersbach and Schneider (2015), Akcigit et al. (2013), Prettner and Werner (2016), and Gersbach et al. (2018).

2015).

The aggregate final good is produced according to the Cobb-Douglas production function

$$Y_t = (H_t^Y)^{1-\alpha} \sum_{i=1}^{A_t} (x_t^i)^\alpha,$$

where H^Y is human capital employed in final goods production (i.e., the stock of knowledge of workers in the final goods sector), x^i is the amount of intermediate good i used in production, $\alpha \in (0,1)$ is the elasticity of final output with respect to the employment of intermediate goods, and A_t refers to the stock of blueprints available in period t. Thus, there are A_t different intermediate goods used in the production of the final good.

Perfect competition ensures that all production factors are paid their marginal value products. The wage per unit of human capital of final goods producers and the price of intermediate good i are therefore given by

$$\begin{aligned} w_t^Y &= (1-\alpha)\frac{Y_t}{H_t^Y}, \\ p_t^{Y,i} &= \alpha \left(H_t^Y\right)^{1-\alpha} \left(x_t^i\right)^{\alpha-1}. \end{aligned}$$

Using the second expression, the profit function in the intermediate goods sector i becomes

$$\pi_t^{x,i} = p_t^{Y,i} x_t^i - x_t^i.$$

Because the intermediate goods producer utilizes a one-for-one technology, the costs of production are equal to the amount of final output employed in the production process. Profit maximization then leads to the optimal pricing rule

$$p_t^i = \frac{1}{\alpha}.$$

In the standard Romer (1990) framework, the price of intermediate good i additionally depends on the capital rental rate. Since we abstract from any sort of physical capital in our model economy, the capital rental rate drops out in the pricing decision of intermediate goods producers. The mark-up of the monopolist only depends on the elasticity of final output with respect to intermediates. An immediate implication is that all intermediate goods producers charge the same mark-up over the price that obtains in a perfectly competitive market such that prices do not depend on the variety i anymore. The total quantity of intermediate goods produced pins down to

$$x_t \;=\; H_t^Y \alpha^{\frac{2}{1-\alpha}}.$$

Aggregate output, operating profits in the intermediate goods sector, and the wage rate per unit of human capital in the final goods sector thus simplify to

$$\begin{aligned} Y_t &= A_t \left(H_t^Y\right)^{\frac{2\alpha}{1-\alpha}}, \\ \pi_t^x &= \frac{1-\alpha}{\alpha} \alpha^{\frac{2}{1-\alpha}} H_t^Y, \\ w_t^Y &= (1-\alpha) A_t \alpha^{\frac{2\alpha}{1-\alpha}}. \end{aligned}$$

The applied research sector follows Prettner and Werner (2016). The stock of patents increases according to the production function

$$A_{t+1} - A_t \;=\; \delta A_t^{\chi} B_t^{\sigma} H_t^A,$$

where—as in Romer (1990) and Jones (1995)—the development of new ideas depends on the stock of already existing ideas, A_t, on the amount of human capital employed in applied research, H_t^A, and on the productivity of scientists in this sector, δ. To analyze the effect of the Scientific Revolution, we also include basic scientific knowledge, B_t, as a necessary input for applied knowledge production. In this setting, χ measures the extent of intertemporal knowledge spillovers (standing on shoulders externality) in the production of applied knowledge, while σ measures the extent of intersectoral knowledge spillovers from basic scientific knowledge to applied research. To focus on a meaningful economic solution, human capital employed in R&D (H_t^A) needs to be non-negative. Thus, the stock of ideas cannot decrease over time.

Already from this formulation, the importance of the Scientific Revolution for the Industrial Revolution becomes obvious. Overall productivity of applied research is given by $\delta A_t^{\chi} B_t^{\sigma}$, which determines the profitability of this sector and the amount of labor that it employs. Without any knowledge of the laws of nature, or, for that matter, with a culture that does not foster scientific inquiry, applied scientists are unproductive and new blueprints/patents cannot be discovered. As a consequence, no applied scientists are employed by firms, which reduces the frequency at which new ideas are developed to zero. This approximates, from a formal perspective, the historical state of economies before the Scientific Revolution (Wootton, 2015). Nature is still arcane and profit-driven R&D is non-existent.

Once this state is overcome and a positive stock of basic scientific knowledge exists, applied knowledge production becomes feasible. In more recent times, applied R&D firms maximize their profits

$$\pi_t^A = p_t^A \delta A_t^\chi B_t^\sigma H_t^A - w_t^A H_t^A,$$

where the first term on the right-hand side is the revenue of selling ideas at the price p_t^A and the second term is the cost of employing human capital H_t^A at the going wage w_t^A per unit of human capital. Maximizing profits with respect to the employment of applied scientists, H_t^A, yields the following relation between wages of applied researchers and their effective productivity

$$w_t^A = p_t^A \delta A_t^\chi B_t^\sigma.$$

Clearly, if applied R&D firms can charge higher prices, p_t^A, for the blueprints that they sell, the wages of applied scientists are higher such that this sector could attract more employees and, thus, produce more ideas. If scientists were more productive (δ were higher), a similar argument held true and employment of applied scientists and thereby technological progress would be faster. Finally, a greater stock of basic scientific knowledge B_t also fosters applied research productivity and leads to faster technological progress and faster economic growth.

As argued above, if $B_t = 0$ holds, then the wages of applied scientists were zero and no technological progress would take place. As the stock of basic scientific knowledge increases, $(B_t - B_{t-1} > 0)$, the productivity of applied knowledge creation rises gradually, such that wages and employment of applied scientists also rise. This, in turn, fosters technological progress and economic growth and catalyzes a takeoff toward sustained knowledge-driven economic development.

Labor market clearing implies that the wage rates of workers in the final goods sector and those of scientists in the applied research sector equalize. Considering that prices of patents, p_t^A, are paid for by operating profits, $\pi_t^x/(1+\bar{r})$, the amount of human capital employed in final goods production is given by

$$H_t^Y = \frac{(1+\bar{r})A_t^{1-\chi}}{\alpha \delta B_t^\sigma}.$$

Turning to the basic scientific research sector, the knowledge base increases according to the production function

$$B_{t+1} - B_t \;=\; \kappa H_t^{\lambda},$$

where, unlike in the applied research sector, deciphering the laws of nature is not compensated.[10] We follow Kremer (1993) and Strulik et al. (2013) in the assumption that the discovery of new basic scientific knowledge depends on the overall number of thinkers in the economy and on their education, i.e., on the stock of aggregate human capital. We also include a stepping-on-toes externality as represented by the inverse of λ, to account for potential duplication of research effort as in Jones (1995). Finally, κ is the productivity in the basic science sector. A situation in which $\kappa = 0$ could be interpreted as capturing a society in which religion or oppressive institutional settings prevent scientific inquiry. Thus, in the words of Mokyr (2016), the "Culture of Growth" would be absent.

Putting all the information together, we arrive at the following system of equations that fully describes the evolution of our model economy over time

$$\begin{aligned}
A_{t+1} &= A_t + \delta A_t^{\chi} B_t^{\sigma} H_t^{A}, & (3)\\
B_{t+1} &= B_t + \kappa H_t^{\lambda}, & (4)\\
h_{t+1} &= \frac{\mu H_t^{E}}{n_t} + \bar{e}, & (5)\\
n_{t+1} &= \frac{(\xi - \theta) w_{t+1} h_{t+1}}{(1 + \beta + \xi)(\psi w_{t+1} h_{t+1} - \eta \bar{e})}, & (6)\\
L_{t+1} &= n_t L_t, & (7)\\
w_{t+1} &= (1 - \alpha) A_{t+1} \alpha^{\frac{2\alpha}{1-\alpha}}, & (8)\\
H_{t+1}^{Y} &= \frac{(1 + \bar{r}) A_{t+1}^{1-\chi}}{\alpha \delta B_{t+1}^{\sigma}}, & (9)\\
H_{t+1}^{E} &= \frac{\eta L_{t+1} n_{t+1}}{w_{t+1}} \frac{\theta \psi w_{t+1} h_{t+1} - \xi \eta \bar{e}}{\eta(\xi - \theta)}, & (10)\\
H_{t+1}^{A} &= (1 - \psi n_{t+1}) h_{t+1} L_{t+1} - H_{t+1}^{Y} - H_{t+1}^{E}, & (11)\\
y_{t+1} &= \frac{\alpha^{\frac{2\alpha}{1-\alpha}} A_{t+1} H_{t+1}^{Y}}{L_{t+1}}. & (12)
\end{aligned}$$

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[10] As argued above, introducing compensation of basic scientific knowledge creation via public funding and taxes is possible but it complicates the model substantially without leading to new insights. For the workings of the model for a modern economy in which basic scientific knowledge is created in publicly funded universities and research facilities see Prettner and Werner (2016). However, these authors are silent on the takeoff to modern economic growth, on the Scientific Revolution, and on the Unified Growth setting.

Here, Equation (3) refers to the equilibrium evolution of the stock of applied knowledge that is needed for the production of differentiated intermediate goods that are, in turn, used in the production of final output. Equation (4) refers to the evolution of the stock of basic scientific knowledge that is an essential input in the production of applied knowledge and lays the foundation for a takeoff toward modern knowledge-based economic growth. Equation (5) describes the evolution of individual human capital depending on the knowledge that children acquire by observing their parents and peers and by the purposeful education investments of parents. The latter only become positive once an economy has surpassed a certain income threshold, facilitating the takeoff toward sustained economic growth. Equation (6) refers to the fertility choice of households that determines population growth. In line with empirical observations, fertility decreases after a certain stage of economic development is reached and then converges to a lower but positive level. Equation (7) captures the evolution of the workforce. Equation (8) delivers the wage rate per unit of human capital that increases with the stock of applied knowledge in the economy. Equations (9)–(11) express employment of human capital in final goods production, education, and R&D, respectively. Finally, Equation (12) denotes per capita GDP that rises with the stock of applied knowledge and with average human capital of the population. Thus, this expression features both of the driving forces of modern economic growth and it is clear that, as long as neither A_t nor h_t grow, there cannot be any sustained increase in per capita income.

In the next section, we use this system to derive the balanced growth path (BGP) analytically. Afterwards, we solve the model numerically to analyze the extent to which basic scientific knowledge drives the takeoff toward sustained long-run growth.

3 The long-run balanced growth path

In the following, we denote the growth rate of a variable x between periods t and $t+1$ by $g_{x,t} = (x_{t+1} - x_t)/x_t$. Along the BGP, the growth rates of all variables and the employment shares remain constant. We observe that positive growth implies ever rising incomes ($\lim_{t\to\infty} w_t h_t = \infty$), such that fertility and education investments along the BGP are equal to

$$n = \frac{\xi - \theta}{(1+\beta+\xi)\psi}, \tag{13}$$

$$e_t = \frac{\theta\psi h_t w_t}{\eta(\xi-\theta)}. \tag{14}$$

Along the BGP, fertility is constant and education is growing with $h_t \cdot w_t$. Considering that consumption, c_t, and savings, s_t, also grow with $h_t \cdot w_t$, the BGP growth rates of individual human capital and of the wage rate need to be determined. The evolution of individual human capital follows the equation

$$h_{t+1} = \frac{\mu\eta e_t n_t L_t}{w_t L_{t+1}} + \bar{e}.$$

Substituting e_t from Equation (14) and using that $L_{t+1}/L_t = n_t$, we arrive at

$$h_{t+1} = \frac{\mu\theta\psi h_t}{\xi-\theta} + \bar{e}. \tag{15}$$

Along the BGP, $\bar{e}$ becomes negligibly small compared with formal schooling as represented by the first term in Equation (15). Therefore, the BGP growth rate of individual human capital can be expressed as

$$g_h = \frac{\mu\theta\psi}{\xi-\theta} - 1. \tag{16}$$

Wage growth solely depends on growth in productive ideas as we know from Equation (8). From Equation (3) we get

$$g_{A,t} = \frac{\delta B_t^{\sigma} H_t^A}{A_t^{1-\chi}}. \tag{17}$$

By definition, the growth rate of A must be constant along the BGP, i.e., we have that $g_{A,t} = g_{A,t+1}$ holds for all t. This occurs if

$$g_{A,t} = \left(\frac{B_{t+1}}{B_t}\right)^{\frac{\sigma}{1-\chi}} \left(\frac{H_{t+1}^A}{H_t^A}\right)^{\frac{1}{1-\chi}} - 1, \tag{18}$$

is fulfilled such that the numerator and the denominator of Equation (17) grow at the same rate. In addition, also the growth rate of B must be constant, i.e., we must have $g_{B,t} = g_{B,t+1}$, which holds for

$$\frac{B_{t+1}}{B_t} = \left(\frac{H_{t+1}}{H_t}\right)^{\lambda}. \tag{19}$$

Next, we derive the expression H_{t+1}/H_t in Equation (19) by substituting for aggregate human capital, using that fertility is constant along the BGP, and taking advantage of Equation (16)

$$\frac{H_{t+1}}{H_t} = \frac{L_{t+1}h_{t+1}}{L_t h_t} = n\frac{\mu\theta\psi}{\xi-\theta}. \tag{20}$$

Inserting Equation (20) into Equation (19), the growth factor of scientific knowledge along the BGP becomes

$$\frac{B_{t+1}}{B_t} = \left(n\frac{\mu\theta\psi}{\xi-\theta}\right)^{\lambda}. \tag{21}$$

Finally, the BGP expression for H^A_{t+1}/H^A_t has to be determined. Along the BGP, the share of human capital in applied research is constant. Therefore, $g_{H^A} = g_H$ has to hold, which implies

$$\frac{H^A_{t+1}}{H^A_t} = \frac{H_{t+1}}{H_t}. \tag{22}$$

Using equations (20), (21), and (22) in Equation (18), the growth rate of applied knowledge along the BGP follows as

$$g_A = \left(n\frac{\mu\theta\psi}{\xi-\theta}\right)^{\frac{1+\lambda\sigma}{1-\chi}} - 1.$$

Substituting in the fertility rate from Equation (13), we finally arrive at the long run BGP growth rate in the modern growth regime:

$$g_A = \left(\frac{\theta\mu}{1+\beta+\xi}\right)^{\frac{1+\lambda\sigma}{1-\chi}} - 1. \tag{23}$$

From this expression, a number of intuitive results that are in line with the standard literature (cf. Strulik et al., 2013; Prettner and Werner, 2016; Baldanzi et al., 2019a) follow. The preference parameter for education, θ, raises individual human capital accumulation of the next generation and reduces fertility, whereas the reverse holds true for the preference parameter for the number of children,

ξ. In line with Strulik et al. (2013), the negative effect of decreasing fertility on aggregate human capital accumulation is overcompensated by the positive effect of accumulating human capital faster. The reason is that a decline in fertility sets free additional resources via the budget constraint that can be used to invest in education. Thus, economic growth increases with θ and decreases with ξ. There is an additional positive effect represented by μ, which is the productivity of teachers. If teachers are more productive, then, for a given investment in education, human capital accumulates faster. This does not affect fertility and only raises human capital accumulation. Thus, technological progress and income growth increase. We summarize these effects in the following proposition.

Proposition 1.

i) An increase in education investments and a decline in fertility as triggered by an increase in the parameter θ or a decrease in the parameter ξ unambiguously raise long-run economic growth because the positive effects of greater education investments on aggregate human capital accumulation outweigh the negative effects of lower fertility.

ii) An increase in teaching productivity, μ, unambiguously raises long-run economic growth.

On top of these results, the long-run growth rate increases with the standing on shoulders effect, λ, because it determines the rate at which basic scientific knowledge accumulates and the long-run growth rate increases with intersectoral knowledge spillovers, σ, because they increase the importance of basic scientific knowledge in the production of new patents. Both of these effects increase the productivity of human capital employed in applied research and thereby raise the rate at which new patents are developed. This, in turn, raises final goods production and income growth. We summarize these results in the following proposition.

Proposition 2. *For $\chi < 1$, long-run economic growth increases unambiguously with faster accumulation of basic scientific knowledge as represented by the terms λ and σ. Thus, basic scientific knowledge is an important driver of economic prosperity.*

This proposition shows the importance of basic scientific knowledge for long-run economic growth in the modern regime. Irrespective of the assumption

$\chi < 1$, which usually implies that long-run growth is only a function of population growth (as in Jones, 1995), our result shows that basic scientific knowledge accumulation and education attain crucial roles in determining economic prosperity.

4 Simulation

4.1 Data

The simulation resembles developments of total factor productivity (TFP), basic scientific knowledge, wage income, the net fertility rate, and individual human capital. Our aim is to use long term data from the United Kingdom that reach back before the Industrial Revolution. We choose the UK as a reference because it is an important forerunner in both the Scientific Revolution and the Industrial Revolution (Galor, 2005, 2011; Wootton, 2015; Mokyr, 2016). In addition, the data coverage and the data quality for the UK both tend to be better over such a long time horizon than for other countries.

We take the data on TFP from FRED (2017) that contains annual TFP growth rates from 1761 onward and is based on Broadberry et al. (2015). Using 25-years averages to eliminate business-cycle fluctuations, we derive the change in the level of TFP over time. We approximate basic scientific knowledge by means of the annual number of cited references from 1651 onward (Bornmann and Mutz, 2015).[11] As explained in Section 2.4, basic scientific knowledge is useful for applied research without, however, being patentable, i.e., it is non-rival and non-excludable. We are well aware of the fact that the number of citations is only a crude indicator for scientific activity but it is the best that we have at our disposal. In addition, more citations would surely imply a higher rate of knowledge diffusion and, thus, indicate a more intensive use of basic scientific research in applied research.

Since we abstract from physical capital in the production process, a direct indicator for economic development in terms of income growth is the wage per worker. As a proxy for this wage rate in the UK, we refer to the real wage of UK craftsmen during 1700–2000 as reported by Clark (2005). Given that the majority of the population was low-skilled historically, this is arguably an

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[11] The annual number of cited references is derived by analyzing the entire spectrum of publications between 1980–2012. A comprehensive overview of scientific journal publishing can be found in Ware and Mabe (2015).

acceptable proxy.

In our model, fertility is the number of children per unisex adult. Choosing fertility in the UK as a comparison would be misleading because of high rates of child mortality, especially before the twentieth century (see Kögel and Prskawetz, 2001; Doepke, 2005). We therefore combine the data set of Ajus and Lindgre (2015) on fertility rates in the UK with the data set of Johansson et al. (2015) on child mortality in the UK to calculate the net reproduction rate. The resulting time series on the net reproduction rate per woman is then transformed into the unisex net fertility rate as used in our model and it covers the period 1800–2000.

Finally, education and with it individual human capital is one of the main driving forces of the transition to sustained economic growth. Thus, our simulation should match the corresponding data. We use the time series on mean years of schooling in the UK from Madsen and Murtin (2017) and apply a Mincer equation as in Hall and Jones (1999) and Prettner et al. (2013) to transform the education data from 1700–2000 into units of human capital.[12]

4.2 Simulation results

For our simulation we have data covering up to 300 years. We choose the following parameter values and initial conditions to match these data. The elasticity of final output with respect to intermediates is set to $\alpha = 0.3$, which is in line with the literature (Jones, 1995; Acemoglu, 2009). Similar to Strulik et al. (2013), the time costs for raising one child are 8%, i.e., $\psi = 0.08$. The yearly individual discount rate is approximately 3%, which corresponds to a discount factor of $\beta = 0.3$ over 40 years (Cropper et al., 2014). All other parameter values are set to fit the data as precisely as possible. In so doing, we set $\xi = 0.35$, $\bar{e} = 0.5$, $\theta = 0.23$, $\eta = 0.1$, $\delta = 1.15$, $\kappa = 0.4$, $\chi = 0.59$, $\mu = 5.4$, $\sigma = 0.15$, and $\lambda = 1$.[13] The initial values for productivity, basic scientific knowledge, and the size of the workforce are taken as $A_0 = 10$, $B_0 = 10$, and $L_0 = 1$.

Figure 1 shows the evolution of TFP over time, with the data (dashed red line) and the model results (solid blue line) being normalized to unity in 1820. Broadly consistent with existing works, TFP is stagnant for decades until the mid-nineteenth century, when the Industrial Revolution altered production pos-

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[12] For further works on the relationship between education, human capital formation, and economic growth, see Hanushek and Kimko (2000); Hanushek and Woessmann (2012a,b).

[13] Note that the intertemporal spillovers, χ, are substantially greater than the intersectoral spillovers, σ. By that we avoid a situation in which basic scientific knowledge is the main driver of economic progress.

sibilities in a fundamental way (Galor and Weil, 2000; Galor, 2005, 2011; Mokyr, 2005; Strulik et al., 2013). Not only does our TFP calibration match the onset of the second Industrial Revolution, it also predicts the length and the magnitude of the takeoff as well as the phase of sustained economic growth from the twentieth century onward reasonably well.

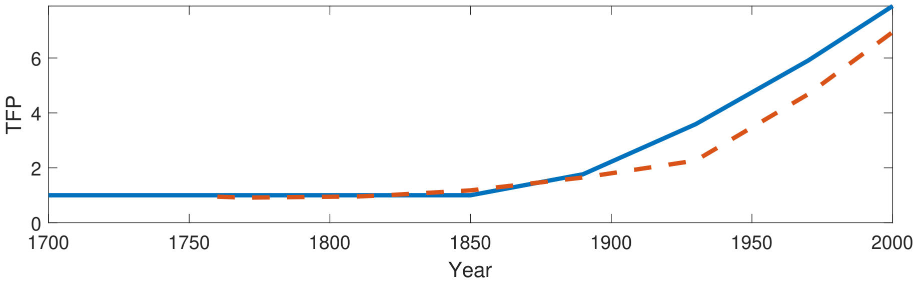

Figure 1: Evolution of TFP (model prediction: solid blue line; data: dashed red line)

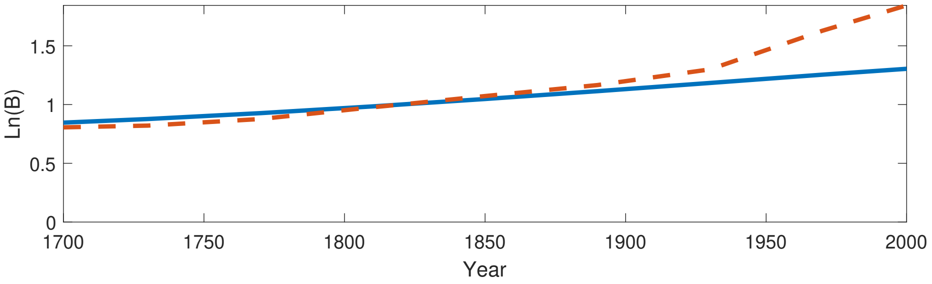

Figure 2: Logarithm of the stock of basic scientific knowledge (model prediction: solid blue line; data: dashed red line)

Which dynamics pave the way to sustained economic growth? Before the onset of the Industrial Revolution, wage income is low. Accordingly, educational investments are low, whereas the fertility rate is high. Productive R&D increases with the stock of existing blueprints, with the stock of basic scientific knowledge, and with the amount of human capital devoted to applied research. For early stages of development, productivity and basic scientific knowledge are small, as is the stock of aggregate human capital. Scientists in the applied research sector are relatively unproductive, which is why the labor force is employed in final goods production, leaving productivity stagnant. A growing population and almost constant education slowly but gradually raise the aggregate stock of human capital. Due to decreasing marginal productivity in the final goods sector and a slow increase in the stock of basic scientific knowledge that comes with the rise in the population size, productivity in the applied researcher sector rises and becomes high enough for researchers to be increasingly attracted into this sector. This is the time when productivity levels start to rise slowly at first and at a faster pace later.

Additional insights are obtained from Figure 2 by taking a closer look at the role of basic scientific knowledge in the process towards the takeoff. While the Industrial Revolution and with it productivity growth started around the turn of the nineteenth century (Ashton, 1997), the takeoff in basic scientific discoveries occurred about one century before. The increase in the growth rate of citations is stronger in the data than the increase in the growth rate of basic scientific knowledge in the model. The main reason is that in our model all basic scientific discoveries are productive, i.e., they raise productivity in applied research immediately. However, as we all tend to know only too well from personal experience, not all scientific research is useful for applications. In particular, over time, basic scientific research has broadened. While in the past, the share of research in the natural sciences was comparatively high, it has decreased as other disciplines, such as economics, have gained importance. Therefore, over time, the share of scientific research that is useful for applied research might have decreased, which could explain the gap between the model predictions and the data.

Wage income is depicted in Figure 3 and is also normalized to unity in 1820. The value derived from the simulation is the available income per worker. As for TFP, we predict the takeoff approximately right. The income gap that emerges during the twentieth century can be attributed to the presence of skilled workers and an associated increase in the skill premium (Acemoglu, 1998). Since our model incorporates production workers as well as scientists, one would expect a steeper increase in wages compared to craftsmen's wages.

In Figure 4, the fertility rate in the model decreases over time and the quantity-quality trade-off induces an even stronger decrease after the takeoff in income growth. Comparing the model outcome to UK data, a similar trend can be observed. Importantly, the fertility rate is high for low levels of development and it decreases below replacement fertility at the end of the twentieth century. The main differences between the series are due to changes in life expectancy over time that our model does not capture. High mortality rates before the onset of the demographic transition slowed down population growth in the UK and in the rest of the world (Human Mortality Database, 2019). This negative pressure on the population size is not present in our model because life expectancy is assumed to be constant. Therefore, for the pre-industrialization area, the model

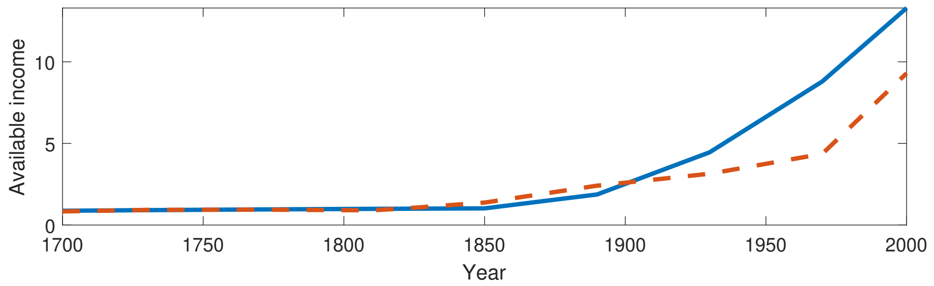

Figure 3: Evolution of available income (model prediction: solid blue line; data: dashed red line)

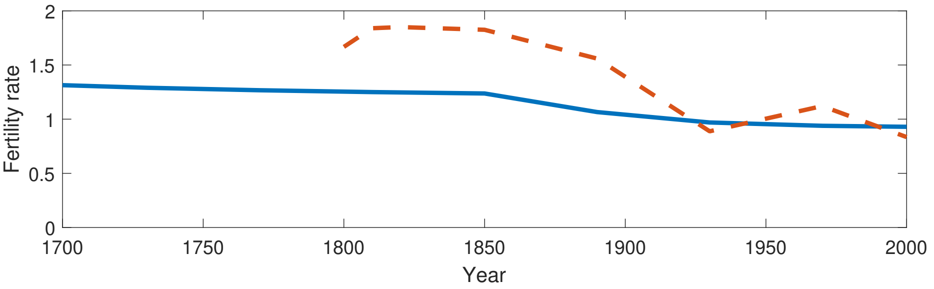

Figure 4: Evolution of fertility (model prediction: solid blue line; data: dashed red line)

fertility rate can be smaller than the fertility rate in the data.

Finally, inspecting Figure 5, individual human capital in the data and in the model increase at the same rate until the Industrial Revolution, after which an increase in the growth rate can be observed in the data that the model does not match fully. One important reason is again the absence of differential skills, which would induce higher investments in eduction of some parts of the population (Acemoglu, 1998). Another reason for the discrepancy might be that the data only reflect the quantity of schooling without controlling for quality, which our model captures.

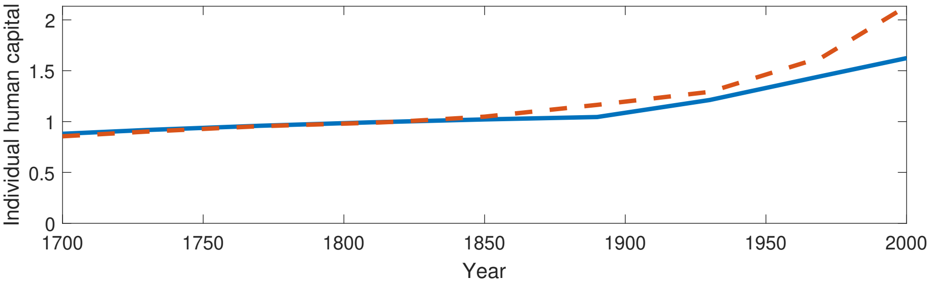

Figure 5: Individual human capital (model prediction: solid blue line; data: dashed red line)

4.3 Comparative statics

So far we have shown the importance of the Scientific Revolution for long-run economic growth from an analytical and from a numerical perspective. Exploiting the model framework, it is now possible to better understand its implications for the timing of the takeoff toward sustained long-run growth by employing a comparative statics analysis. Changing the evolution of the stock of basic scientific knowledge and its inclusion in applied research, we can analyze how a different timing of scientific discoveries might have altered economic progress and the timing of the takeoff.

In Figure 6, we show the evolution of wages given different assumptions on the productivity of thinkers in the basic scientific research sector. With the exception of κ and B_0, all parameter values and initial values are as in Section 4.2. The baseline case of $\kappa = 0.4$ is displayed as the red line. By varying κ, basic scientific knowledge accumulates at a different rate, which, in turn, affects the productivity of scientists working in applied R&D and, thus, economic progress.

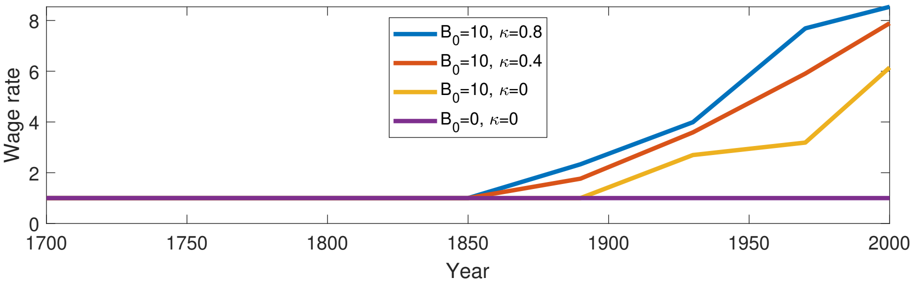

Figure 6: Wages for different values of κ and initial levels of B_0

Overall, the rate of economic growth increases with κ such that the takeoff to long-run growth is steeper. The logic behind is that more basic scientific knowledge is available, which makes applied research more profitable. By contrast, the timing of the Industrial Revolution is postponed with a decrease of κ. In the extreme case of $\kappa = 0$, B is constant over time at the initial value. In this case the takeoff is postponed by one generation (as shown by the yellow line). Since productivity of scientists in the applied research sector is determined not solely by scientific knowledge but also by education, i.e., human capital, the economy reaches the threshold at which applied research becomes profitable later. Eventually, better educated scientists are able to compensate the lack of growth in basic scientific knowledge and the Industrial Revolution takes its course. While a setback of one generation might seem little over the course of human history, such a setback would imply that we had an income level today similar to the one in 1980, which is substantially less.

Changing the intersectoral spillovers, σ, and keeping everything else constant, also affects wages and follows a very similar logic. As obvious from Figure 7, the timing of the takeoff crucially hinges on the degree of transmission of scientific knowledge in applied knowledge production. For low spillovers, i.e., if the transmission of scientific advances to the development of productive R&D is lower (e.g., in case of poor knowledge diffusion or for cultural reasons), the takeoff in wages occurs later. Again, the reason is that basic scientific knowledge increases the productivity of applied researchers. If there is a fast rate of scientific discoveries but these discoveries are not considered in applied research, the productivity in and profitability of developing new blueprints is low, which delays the takeoff. These observations lead to the following remark.

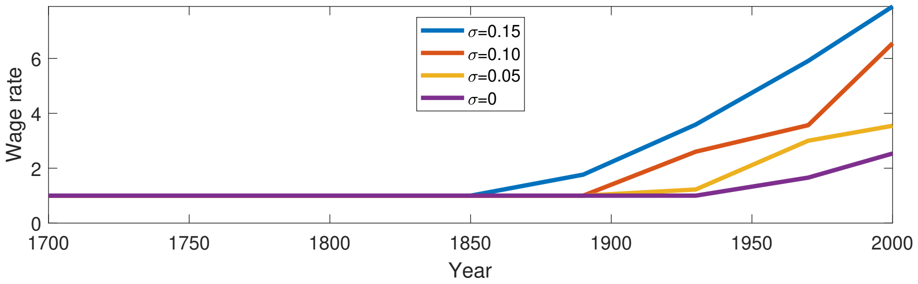

Figure 7: Wages for different values of σ

Remark 1. *Basic scientific research and with it the Scientific Revolution play a crucial role in the timing of the Industrial Revolution. A postponement of the Scientific Revolution or a reduced transmission of basic scientific knowledge to applied research would have delayed economic progress severely.*

As discussed in Remark 1, *growth* in basic scientific knowledge is not necessary for the economy to take off (as long as the level of B_0 is positive) but a lack of it can postpone the takeoff substantially. What happens if not only g_B were zero but also B_0? Such a scenario is shown in Figure 6. The economy would not take off at all because without any understanding of the natural laws and of scientific inquiry, no productive R&D is possible, leaving the economy stagnant indefinitely. We emphasize this in the following remark.

Remark 2. *Scientific knowledge is indispensable for an economy to take off because productive applied R&D requires scientists to have, at least, a basic understanding of the laws of nature and of scientific inquiry.*

5 Conclusions

We propose a novel Unified Growth model that sheds light on the role of the Scientific Revolution in the process of the convergence toward a takeoff to sustained economic growth. We show that the accumulation of basic scientific knowledge (comprising knowledge about the laws of nature, knowledge about the scientific method, and knowledge about the ways to disseminate ideas) and its application in applied research is a crucial driver of economic progress in the long run. If the stock of scientific knowledge does not grow or if the transmission of scientific achievements to applied research is limited, the takeoff to sustained economic growth will be delayed. This fits the historical evidence that over time British endowment of science-based knowledge was growing, but only during the second Industrial Revolution around the 1850s, this basic knowledge started to matter. In the extreme case in which scientific inquiry is prevented altogether, e.g., for religious reasons or by oppressive rulers, the takeoff to sustained growth might be delayed indefinitely.

Our theory can explain why some countries and regions experienced the fertility transition and the takeoff to modern economic growth much later than others. For example, China was technologically more advanced than European countries in the middle ages but then the Ming Dynasty decided to pursue isolationist policies. Science did not progress as quickly as previously and China was eventually overtaken by Europe, where the Industrial Revolution occurred first. In fact China, which was among the richest countries in the world around 1000 AD became one of the poorest countries in the world in the midst of the twentieth century (Morris, 2010). We believe that our proposed framework can be helpful in understanding the reasons why this was the case.

As far as promising avenues for further research are concerned, a need exists for better data on the calibration of the model for the time period 1500 onward. Particularly helpful would be a database that allowed the quantification of major scientific insights and major breakthroughs in applied knowledge creation over that time period. Another interesting topic is to analyze the extent to which institutions and knowledge interacted in the emergence of the *Culture of Growth.*

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