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The scientific revolution and its implications for long-run economic development

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ABSTRACT

We analyze the role of the Scientific Revolution in the takeoff to sustained long-run economic development. Basic scientific knowledge is a necessary input in the production of applied knowledge, which, in turn, fuels productivity growth and leads to rising incomes. Subsequently, rising incomes instigate a fertility transition and foster education investments. Together, the increasing stocks of basic scientific knowledge and human capital, and the concomitant reduction in fertility enable economic development. In regions where scientific inquiry is severely constrained—for example, due to religious reasons or due to oppressive rulers—the takeoff is delayed or may not occur at all. This shows the importance of investing in basic scientific inquiry when trying to achieve long-run economic prosperity. Our framework could contribute to the understanding of why sustained economic development emerged first in Europe and not in technologically more advanced China.

Nations and their economies grow in large part because they increase their collective knowledge about nature and their environment, and because they are able to direct this knowledge toward productive ends (Mokyr, 2016).

1. Introduction

Much has been written about the causes of the Industrial Revolution and the question why it took place in Britain first and not, for instance, in China, which was the technological leader in medieval times. Although it is widely accepted that the explanation for Britain's success must be rooted in the development and improvement of new technologies, researchers disagree on the fundamental causes of the uptick in technological progress in Britain and Europe in the 19th century. Central to this debate is the disputed role of science. Previous findings mainly focused on education or literacy as skill measures. However, what seems more important is the "density in the upper tail" of the skill distribution (Mokyr, 2002; Mokyr, 2016; Wootton, 2015; Jacob, 2014). Jacob (2014) 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] Thus, to develop important new technologies, it is not the general skill level of the population that matters, but the "ingenuity and technical ability of a minority" (Mokyr & Voth, 2009, p. 35). Moreover, (Mokyr, 2002) stresses that the Enlightenment had a strong impact on the first Industrial Revolution because it was not only conducive to the production of more useful knowledge but also because it reduced access costs to knowledge. For example, the "Republic of Letters", a group of scientists and intellectuals who discussed and shared ideas intensively, changed the way of knowledge dissemination, which led to the establishment of the first scientific journals (Mokyr, 2016).

Although Allen (2011) sees the role of relative factor prices as most important for the success of British innovations, he agrees

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

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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 regarding 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 development from the 1850s onward. This is also supported by recent research of Squicciarini and Voigtländer (2015), who have shown that the presence of knowledge elites played an important role for the French industrial take-off. For Prussia, Cinnirella and Streb (2017), have shown 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 economic development, in the subsequent twentieth century, the quality of basic education was important for worker's productivity and R&D processes. For France, Diebolt, Le Chapelain, and Menard (2019, 2021) provide similar evidence, showing that a shift in the kind of skills required occurred in the second half of the nineteenth century and that steam technology adoption in France was not deskilling, but instead raised the demand for new skills adapted to the development of French industries. We aim at contributing to this debate by formalizing these ideas and proposing a unified framework that incorporates (i) basic scientific knowledge creation, (ii) a fertility transition that instigates subsequent mass education and human capital accumulation, and (iii) endogenous R&D-driven technological progress that propels long-run economic development.

Our framework builds on two central foundations. The Unified Growth Theory invented by Galor and Weil (2000) and further developed and extended by Galor (2005), Galor (2010), and Galor (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. By contrast, 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 analyze the interactions between basic scientific research and applied research over the very long run and how these interactions could facilitate a takeoff toward sustained economic development.

We aim to fill this gap by merging the two strands of Unified Growth Theory and R&D-based endogenous growth theory with both basic scientific knowledge creation and the accumulation of 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 investment in education becomes positive and a fertility transition sets in (see, for example, Strulik et al., 2013; Diebolt & Perrin, 2017). The associated increase in formal schooling and human capital accumulation is then one of the central drivers of the takeoff toward sustained economic development.[4]

In contrast to the standard Unified Growth literature, however, our model features an additional engine for the takeoff. This engine 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 R&D sector (Romer, 1990; Jones, 1995). Applied R&D becomes profitable and operative once the stock of basic scientific knowledge in a society is large enough. 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 gets accumulated, the more productive is applied R&D and the earlier the takeoff to sustained innovation-driven development occurs.

Overall, our approach fits to the historical evidence that British science-based knowledge started among a small elite, from which it spread and grew over time, and that, particularly during the second Industrial Revolution, when steam and coal occupied center stage, this basic scientific knowledge mattered a great deal in fostering technological progress. The *sustained* takeoff in applied R&D cannot occur if there is an insufficient 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 innovation-driven economic development as described by Wootton (2015) and Mokyr (2016).

We believe that the suggested framework enables a more sophisticated understanding of the development 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 growth. As such, our framework provides an explanation why Britain/Europe experienced the Industrial Revolution first.[5]

Our paper is closely related to the seminal work of O'Rourke, Rahman, and Taylor (2013) who propose a skill-biased technical change model with a demographic and economic transition that is ultimately driven by exogenously growing basic knowledge. In their framework, however, the Industrial Revolution happens inevitably, which is not the case in our model. This difference allows us to assess the extent to which the underlying dynamics are driven by the accumulation of basic knowledge. Additional differences are that we model formal education explicitly in a separate education sector and that we solve for the long-run balanced

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[2] For other important contributions, see the works of (Jones, 2001; Kögel & Prskawetz, 2001; Hansen & Prescott, 2002; Tamura, 2002; Galor & Moav, 2002; Galor & Moav, 2004; Galor & Moav, 2006; de la Croix & Doepke, 2003; Doepke, 2004; Cervellati & Sunde, 2005; Cervellati & Sunde, 2011; Strulik & Weisdorf, 2008; Strulik, 2014; Strulik, 2017; Galor, Moav, & Vollrath, 2009; Lanz, Dietz, & Swanson, 2017).

[3] For a non-exhaustive list of contributions to the theory and empirics of endogenous, semi-endogenous, and Schumpeterian growth theory, see, for example, (Grossman & Helpman, 1991,Kortum, 1997), (Dinopoulos & Thompson, 1998,Peretto, 1998), (Segerström, 1998,Young, 1998), (Howitt, 1999,Dalgaard & Kreiner, 2001), (Strulik, 2005,Bucci, 2008), (Peretto & Saeter, 2013,Strulik, Prettner, & Prskawetz, 2013), (Prettner, 2014,Minniti & Venturini, 2017), and (Herzer, 2022).

[4] This mechanism is consistent with (Diebolt, Menard, & Perrin, 2017) who study the relationship between fertility and education based on French county data. They find a causal effect of fertility decline on education. Diebolt, Mishra, and Perrin (2021) add that for stable long-run growth, it is important that parents educate their girls, which has a particularly strong impact on declining fertility. This is also supported by Minasyan, Zenker, Klasen, and Vollmer (2019)'s meta-study on the link between gender inequality in education and per capita economic growth. Relying on a structural estimation technique, (de la Croix & Perrin, 2017) quantify the joint decision between fertility and education by disentangling how much of it is explained by rational choice rather than social norms. The authors find that, in the case of France, the rational choice model explains 38 percent of the variation of fertility over time and across counties, and 71 percent and 83 percent of school enrollment of boys and girls, respectively.

[5] A complementary mechanism is described by Cantoni and Yuchtman (2014) who show that the emergence of markets was fostered by the establishment of universities in medieval Germany.

growth path analytically, which allows us to show the importance of basic scientific knowledge creation even in the very long run.

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

2. Effects of the Scientific Revolution on long-run economic development: theoretical analysis

In this section, we describe our model framework. We propose an R&D-based growth model in the vein of Romer (1990) and Jones (1995) into which we incorporate an endogenous fertility-education decision (Becker & Lewis, 1973; Galor & 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 (O'Rourke et al., 2013; Prettner & Werner, 2016).

2.1. Basic assumptions

Consider an 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.[6] We conceptualize adults as single-sex parents[7] 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 development.

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 (Strulik et al., 2013; Bloom et al., 2020). As in standard Unified Growth models, this is another main engine for the takeoff to sustained economic development.[8]

2.2. Consumption side

Individuals derive utility from consumption during adulthood, c_t, from consumption when old, $c_{t+1} = s_t(1+\bar{r})$, where s_t are savings and $\bar{r}$ is the rate of return on assets, from having children, n_t, and from the education investments in their children, e_t.[9] For simplicity, we assume a small open economy perspective such that the rate of return on assets is determined on the world market. Utility is logarithmic and given by

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

where β is the discount factor, ξ refers to the preference of parents for the number of children, and θ to the preference of parents for children's education. In line with the Unified Growth literature, $\bar{c}$ reflects the level of subsistence in terms of consumption. If income is below the level that ensures a household's subsistence consumption can be satisfied, the household would starve (see, for example, Galor & Weil, 2000; Galor, 2005; Galor, 2011). The parameter $\bar{e}$, in turn, represents a minimum informal education level that children acquire through observation and learning-by-doing even if parents do not invest in the formal education of their children (see Strulik et al., 2013). The presence of this parameter implies the realistic feature that education is a luxury good. As a consequence, it does not pay off for poor households to invest in formal education, while, with rising income levels, investing in formal education of the children becomes increasingly worthwhile.

The parameter β, which measures patience, could also be interpreted to capture the probability of dying between adulthood and old age. This probability, in turn, determines life expectancy. A small β would therefore fit well to most of human history when life was "nasty, brutish, and short" as mentioned by Thomas Hobbes.[10]

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[6] For simplicity, we abstract from public pension schemes and from changing life expectancy because public pension schemes are a rather new phenomenon (Hannah, 1986; Boersch-Supan & Wilke, 2004; Lehmann-Hasemeyer & Streb, 2018) and the implementation of endogenous life expectancy would complicate the model without altering the central results. For Unified Growth models encompassing lifetime uncertainty, see, for example, (Cervellati & Sunde, 2005; Cervellati & Sunde, 2015 & Tamura, 2006).

[7] The assumption of single-sex parents allows us to abstract from modeling intra-family bargaining processes and, thus, to focus on the macroeconomic effects. For contributions that investigate marriage and intra-household decision processes in more detail, see, for example, (de la Croix & Vander Donckt, 2010; Doepke & Kindermann, 2019; Bloom, Kuhn, & Prettner, 2020; and Perrin, 2022). Related to long-run growth outcomes, (Diebolt & Perrin, 2013; Diebolt & Perrin, 2019) show how the acceleration of skill-biased technological progress generates a positive externality on gender equality. Higher gender equality (via female empowerment) reinforces individuals' incentives to acquire skilled human capital. Rising educational investments, in turn, increase the opportunity cost of having children and lead to a decline in fertility. Ultimately, the process generates a positive feedback loop where women's empowerment is at the origin of the demographic transition and is one of the key forces behind the transition to sustained economic growth. Using a similar approach, (Prettner & Strulik, 2017) analyze how the gap in the preferences between men and women regarding the number of children can lead to faster economic growth. In their model, women care more about their children's education, while men care more about the number of children. Women's empowerment then has the potential to instigate an escape from the Malthusian trap such that fertility declines, human capital accumulates, and income per capita increases. The crucial role of women for economic growth has also been confirmed in recent empirical studies, for example, by Dahlum, Knutsen, and Mechkova (2022) and Baten and de Pleijt (2022). For an overview of the literature on the role of female empowerment in the process of economic development see also (Merouani & Perrin, 2022).

[8] The increase in economic growth that is triggered by these dynamics is further reinforced by the demographic dividend, i.e., that a decrease in fertility reduces youth dependency and thereby increases the share of the working age population (Bloom & Williamson, 1998; Bloom, Canning, & Sevilla, 2003). This raises per capita GDP mechanically but it also induces additional effects if the gains of the dividend are invested in growth-promoting areas such as education, health, and infrastructure (Bloom, Kuhn, & Prettner, 2017; Cruz & Ahmed, 2018).

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

[10] Note that increasing patience would induce similar behavioral changes as increasing life expectancy (Chakraborty, 2004; Baldanzi, Prettner, & Tscheuschner, 2019).

Taken together, our formulation captures the situation in agrarian pre-industrial societies—in which children mainly learned by working alongside their parents and peers and life expectancy was low—rather well.

The 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 & Weil, 2000; Blackburn & Cipriani, 2002; Galor, 2005; Galor, 2011). The product $w_t h_t$ is labor income 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 remainder 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. This setting implies a quality-quantity tradeoff: on the one hand, having more children raises household utility; on the other hand, having more children reduces the amount of resources that can be devoted to the education of each child.[11]

We assume that initial income is sufficient to cover subsistence consumption ($w_0 h_0 > \bar{c}$) because otherwise people would starve and the economy would cease to exist. Maximizing (1) subject to (2) yields the following optimality conditions for consumption and savings

$$c_t = \frac{(\beta+\xi)\bar{c} + w_t h_t}{1+\beta+\xi} \qquad s_t = \frac{\beta(w_t h_t - \bar{c})}{1+\beta+\xi}, \tag{3}$$

while we have to distinguish between the following cases for the fertility and education choices

$$n_t = \begin{cases} \frac{\xi(h_t w_t - \bar{c})}{\psi(1+\beta+\xi)h_t w_t} & \text{for } h_t w_t \leqslant \frac{\eta\xi\bar{e}}{\theta\psi}, \\ \frac{(\xi-\theta)(h_t w_t - \bar{c})}{(1+\beta+\xi)(\psi h_t w_t - \eta\bar{e})} & \text{otherwise}. \end{cases} \tag{4}$$

$$e_t = \begin{cases} 0 & \text{for } h_t w_t \leqslant \frac{\eta\xi\bar{e}}{\theta\psi}, \\ \frac{\theta\psi h_t w_t - \eta\xi\bar{e}}{\eta(\xi-\theta)} & \text{otherwise}. \end{cases} \tag{5}$$

As is intuitive, consumption and savings both increase with income. While savings increase with the discount factor, the opposite holds true for consumption. With respect to fertility, a hump-shaped pattern emerges. When income $h_t w_t$ is barely above the subsistence level $\bar{c}$, fertility rises with increases in income as in Galor and Weil (2000). At later stages of development, when income surpasses the threshold $h_t w_t = \eta\xi\bar{e}/(\theta\psi)$, fertility converges to a lower level. The reason is that a quality-quantity tradeoff between family size and human capital as in Becker, Murphy, and Tamura (1990) sets in. Since education is costly, its increase implies that households can afford fewer children. Overall, households or societies with a low preference for education (θ), exhibit relatively high levels of fertility and vice versa. Using the rule of L'Hospital, we can show that fertility stays constant in the long-run limit for a rising income level, which is in line with the literature (Galor & Weil, 2000; Galor, 2005; Galor, 2011; Strulik et al., 2013; Bloom et al., 2020):

$$\lim_{h_t w_t \to \infty} \frac{(\xi-\theta)(h_t w_t - \bar{c})}{(1+\beta+\xi)(\psi h_t w_t - \eta\bar{e})} = \frac{\xi-\theta}{(1+\beta+\xi)\psi}. \tag{6}$$

For fertility to be positive, $\xi > \theta$ has to hold. This parameter restriction is reasonable because it rules out the situation in which parents would want to invest in the education of their children before choosing to have children at all.

As far as education investments are concerned, they cannot be negative. Thus, a corner solution of $e_t = 0$ emerges for low income levels. Since education is a luxury good, households with low incomes spend their resources on consumption and fertility while their children would still acquire the basic level of human capital through $\bar{e}$. Consistent with the explanations from above, parents only invest in the education of their children after wage income has surpassed the threshold given by $\eta\xi\bar{e}/\theta\psi$.

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 cost of education (the salaries of teachers) and isolate the implied employment level of teaching personnel. Aggregate education 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 education expenditures amount to education expenditures per child ($\eta \cdot e_t$), multiplied by the number of children (n_t), and aggregated over all households that invest in education (L_t). The cost of education is represented by the wage bill of teachers given by $H_t^E w_t$, with H_t^E being the aggregate human capital employed in education. Equating education expenditures with education cost 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 effective schooling. Dividing economy-wide effective 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 the case of a poor economy with a low income level, education expenditures are zero and no teachers are employed. 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 science sector. The aggregate final good is produced under perfect competition by workers using intermediate goods as inputs. The intermediate goods, in turn, are 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 & Howitt, 2009). For the monopolist to produce the intermediate good, it needs to buy a corresponding blueprint from the applied research sector. The monopolist collects the necessary funds by issuing shares that households buy with their savings. For simplicity, we abstract from physical capital in the production process. The inclusion of physical capital as a second saving vehicle would not alter our main findings but it would complicate the model substantially (see also Galor & Weil, 2000).

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[11] If, instead, the cost 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 empirically (Li & Zhang, 2007; Galor, 2011; Fernihough, 2017) would vanish.

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 ideas 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 their peers. In modern times, basic research is typically funded by governments and conducted in research institutes and universities.[12] Since we do not want to overburden our model, we abstract from the public funding of modern basic science and instead 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 level of education (Strulik et al., 2013). Scientists may 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 scientists in the applied research sector to create new patents/blueprints (Mokyr, 2002; Mokyr, 2005; Mokyr, 2016; Wootton, 2015). More generally, the output of the basic scientific sector could be interpreted to comprise everything that makes it easier to discover new technologies and accumulate more basic and applied knowledge. In that sense, the output of this sector is 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, 2015).

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

$$Y_t = \left(H_t^Y\right)^{1-\alpha} \sum_{i=1}^{A_t} \left(x_t^i\right)^{\alpha}, \tag{7}$$

where H^Y is human capital employed 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 use 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 process 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

$$w_t^Y = (1-\alpha)\frac{Y_t}{H_t^Y}, \tag{8}$$

$$p_t^{Y,i} = \alpha\left(H_t^Y\right)^{1-\alpha}\left(x_t^i\right)^{\alpha-1}. \tag{9}$$

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 cost of production is equal to the amount of final output employed in the production process. Profit maximization then leads to the optimal pricing rule

$$p_t^i = \frac{1}{\alpha}. \tag{10}$$

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 of 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

$$x_t = H_t^Y \alpha^{\frac{2}{1-\alpha}}. \tag{11}$$

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

$$Y_t = A_t\left(H_t^Y\right)^{\frac{2\alpha}{1-\alpha}}, \tag{12}$$

$$\pi_t^x = \frac{1-\alpha}{\alpha}\alpha^{\frac{2}{1-\alpha}} H_t^Y, \tag{13}$$

$$w_t^Y = (1-\alpha)A_t \alpha^{\frac{2\alpha}{1-\alpha}}. \tag{14}$$

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

$$A_{t+1} - A_t = \delta A_t^{\chi} B_t^{\sigma} H_t^A, \tag{15}$$

where—as in Romer (1990) and Jones (1995)—the creation 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 in applied knowledge production. The parameter $\overline{B}$ captures a minimum level of basic scientific knowledge that is necessary for applied knowledge production. We interpret B_t as being the level of basic scientific knowledge over and above a minimum level $\overline{B}$. Thus, it is necessary to surpass the level of minimal basic scientific knowledge in the economy, otherwise $A_{t+1} - A_t$ would be zero and no new applied knowledge was produced. In Eq. (15), $\chi \in (0,1)$ measures the extent of intertemporal knowledge spillovers in the production of applied knowledge (the standing on shoulders externality), while $\sigma \in (0,1)$ measures the extent of intersectoral knowledge spillovers from basic scientific knowledge to applied research.

At this stage, 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 a certain knowledge of the laws of nature, or, for that matter, with a culture that does not foster scientific inquiry, basic scientific knowledge is below $\overline{B}$. In this case, 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

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[12] For the modeling of a modern basic research sector along these lines, see, for example, (Gersbach, Schneider, & Schneller, 2012; Akcigit, Hanley, & Serrano-Velarde, 2021; Gersbach & Schneider, 2015; Prettner & Werner, 2016; Gersbach, Sorger, & Amon, 2018).

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 solid stock of basic scientific knowledge exists, applied knowledge production becomes feasible. 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

$$w_t^A = p_t^A \delta A_t^{\chi} B_t^{\sigma}. \tag{16}$$

Clearly, if applied R&D firms can charge higher prices, p_t^A, for the blueprints that they sell, the wages of applied scientists would be higher such that this sector could attract more employees and, thus, produce more ideas. If scientists are more productive (δ is higher), a similar argument holds 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 basic scientific knowledge is below $\overline{B}$, the wages of applied scientists are zero. In this case, employment in applied research is zero and no technological progress could take place. As the stock of basic scientific knowledge increases and surpasses the level $\overline{B}$, the productivity in applied knowledge creation becomes positive and rises gradually afterwards. Thus, wages and employment of applied scientists also rise, which, 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 the price of a patent, p_t^A, is paid for by operating profits, $\pi_t^x/(1+\bar{r})$, the amount of human capital employed in final goods production is given by

$$H_t^Y = \frac{(1+\bar{r})A_t^{1-\chi}}{\alpha\delta B_t^{\sigma}}. \tag{17}$$

Turning to the basic science sector, the knowledge base of the economy increases according to the production function

$$B_{t+1} - B_t = (1-\gamma)\kappa H_t^{\lambda}, \tag{18}$$

where, unlike in the applied research sector, deciphering the laws of nature is not compensated.[13],[14] We follow Kremer (1993) and Strulik et al. (2013) in assuming 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 and γ refers to the willingness of the authorities to accept new ideas. A situation in which $\gamma = 0$ refers to an "enlightened society" that accepts scientific inquiry and does not hinder progress. By contrast, a situation in which $\gamma = 1$ represents a society in which religion or oppressive institutional settings prevent scientific inquiry. Thus, in the words of Mokyr (2016), there is no *Culture of Growth* in this case.

Putting all the information together, we arrive at the following system of equations that fully describes the evolution of our model economy in the early regime when parents do not yet invest in the education of their children:

$$A_{t+1} = A_t + \delta A_t^{\chi} B_t^{\sigma} H_t^A, \tag{19}$$

$$B_{t+1} = B_t + (1-\gamma)\kappa H_t^{\lambda}, \tag{20}$$

$$h_{t+1} = \bar{e}, \tag{21}$$

$$n_{t+1} = \frac{\xi(h_{t+1}w_{t+1} - \bar{c})}{\psi(1+\beta+\xi)h_{t+1}w_{t+1}}, \tag{22}$$

$$L_{t+1} = n_t L_t, \tag{23}$$

$$w_{t+1} = (1-\alpha)A_{t+1}\alpha^{\frac{2\alpha}{1-\alpha}}, \tag{24}$$

$$H_{t+1}^Y = \frac{(1+\bar{r})A_{t+1}^{1-\chi}}{\alpha\delta B_{t+1}^{\sigma}}, \tag{25}$$

$$H_{t+1}^E = 0, \tag{26}$$

$$H_{t+1}^A = (1-\psi n_{t+1})h_{t+1}L_{t+1} - H_{t+1}^Y, \tag{27}$$

$$y_{t+1} = \frac{\alpha^{\frac{2\alpha}{1-\alpha}} A_{t+1} H_{t+1}^Y}{L_{t+1}}. \tag{28}$$

After education investments of parents turned positive, the economy enters the modern regime, which is fully described by the following dynamic system

$$A_{t+1} = A_t + \delta A_t^{\chi} B_t^{\sigma} H_t^A, \tag{29}$$

$$B_{t+1} = B_t + (1-\gamma)\kappa H_t^{\lambda}, \tag{30}$$

$$h_{t+1} = \frac{\mu H_t^E}{n_t} + \bar{e}, \tag{31}$$

$$n_{t+1} = \frac{(\xi-\theta)(w_{t+1}h_{t+1} - \bar{c})}{(1+\beta+\xi)(\psi w_{t+1}h_{t+1} - \eta\bar{e})}, \tag{32}$$

$$L_{t+1} = n_t L_t, \tag{33}$$

$$w_{t+1} = (1-\alpha)A_{t+1}\alpha^{\frac{2\alpha}{1-\alpha}}, \tag{34}$$

$$H_{t+1}^Y = \frac{(1+\bar{r})A_{t+1}^{1-\chi}}{\alpha\delta B_{t+1}^{\sigma}}, \tag{35}$$

$$H_{t+1}^E = \frac{\eta L_{t+1} n_{t+1}}{w_{t+1}} \frac{\theta\psi w_{t+1}h_{t+1} - \xi\eta\bar{e}}{\eta(\xi-\theta)}, \tag{36}$$

$$H_{t+1}^A = (1-\psi n_{t+1})h_{t+1}L_{t+1} - H_{t+1}^Y - H_{t+1}^E, \tag{37}$$

$$y_{t+1} = \frac{\alpha^{\frac{2\alpha}{1-\alpha}} A_{t+1} H_{t+1}^Y}{L_{t+1}}. \tag{38}$$

Here, Eqs. (19) and (29) refer to the equilibrium evolution of the stock of applied knowledge that is needed for the production of differentiated intermediate goods. Eqs. (20) and (30) refer 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 development. Eqs. (21) and (31) describe 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 in the modern regime when the economy has surpassed the income threshold above which parents invest in the education of their children, which, in turn, facilitates the takeoff toward sustained economic development. Eqs. (22) and (32) refer to the fertility choice

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[13] 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 mechanisms of the model when basic scientific knowledge is created in publicly funded universities and research facilities, see (Prettner & Werner, 2016).

[14] In future research, it would be interesting to link the evolution of basic knowledge to the prior evolution of different forms of human capital (cf. Squicciarini & Voigtländer, 2015; de la Croix, Doepke, & Mokyr, 2018). This would need to be done in a more disaggregated model in which we could distinguish between different types of human capital such as high-skilled workers versus low-skilled workers, and, particularly, with a focus on workers in the upper tail of the skill distribution (de la Croix, Docquier, Fabre, & Stelter, 2020).

of households that determines population growth. In line with empirical observations in O'Rourke et al. (2013, Fig. 4), fertility increases with income in the early regime but decreases after a certain stage of economic development is reached. After that, fertility converges to a lower level. Eqs. (23) and (33) capture the evolution of the workforce depending on population growth. Eqs. (24) and (34) display the wage rate per unit of human capital that increases with the stock of applied knowledge in the economy. Eqs. (25)–(27) and (35)–(37) express employment of human capital in final goods production, formal education, and R&D. In the early regime, employment in formal education is zero such that there is no human capital accumulation. By contrast, in the modern regime, parents invest in the education of their children such that human capital accumulation takes place. Finally, Eqs. (28) and (38) denote 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, sustained increases in per capita income are impossible.

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

2.5. 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 balanced growth path, 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 balanced growth path are equal to

$$n = \frac{\xi - \theta}{(1+\beta+\xi)\psi}, \tag{39}$$

$$e_t = \frac{\theta\psi h_t w_t - \eta\xi\bar{e}}{\eta(\xi - \theta)}. \tag{40}$$

Thus, in the long run, fertility is constant and education is growing with income, $h_t \cdot w_t$. Considering that consumption, c_t, and savings, s_t, also grow with income, $h_t \cdot w_t$, the growth rates of individual human capital and of the wage rate need to be determined to solve for the balanced growth path. From Subsection 2.3, we know that the evolution of individual human capital follows the difference equation

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

Substituting e_t from Eq. (40) and using that $L_{t+1} = L_t n_t$, we arrive at

$$h_{t+1} = \frac{\mu\theta\psi h_t}{\xi - \theta} - \frac{\mu\eta\xi\bar{e}}{(\xi - \theta)w_t} + \bar{e}. \tag{41}$$

Along the balanced growth path, wages (w_t) and human capital (h_t) grow such that the second and the third terms of Eq. (41) become negligibly small compared with formal schooling as represented by the first term. Therefore, the growth rate of individual human capital converges to

$$g_h = \frac{\mu\theta\psi}{\xi - \theta} - 1. \tag{42}$$

Wage growth solely depends on growth in productive ideas as we know from Eq. (34). From Eq. (29), we get

$$g_{A,t} = \frac{\delta B_t^{\sigma} H_t^A}{A_t^{1-\chi}}. \tag{43}$$

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

$$g_{A,t} = \left(\frac{B_{t+1}}{B_t}\right)^{\frac{\sigma}{1-\chi}} \left(\frac{H_{t+1}^A}{H_t^A}\right)^{\frac{1}{1-\chi}} - 1 \tag{44}$$

is fulfilled such that the numerator and the denominator of Eq. (43) 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

$$\frac{B_{t+1}}{B_t} = \left(\frac{H_{t+1}}{H_t}\right)^{\lambda}. \tag{45}$$

Next, we derive the expression H_{t+1}/H_t in Eq. (45) by substituting for aggregate human capital, using that fertility is constant along the balanced growth path, and taking advantage of Eq. (42)

$$\frac{H_{t+1}}{H_t} = \frac{L_{t+1}h_{t+1}}{L_t h_t} = n\frac{\mu\theta\psi}{\xi - \theta}. \tag{46}$$

Inserting Eq. (46) into Eq. (45), the growth factor of basic scientific knowledge along the balanced growth path becomes

$$\frac{B_{t+1}}{B_t} = \left(n\frac{\mu\theta\psi}{\xi - \theta}\right)^{\lambda}. \tag{47}$$

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

$$\frac{H_{t+1}^A}{H_t^A} = \frac{H_{t+1}}{H_t}. \tag{48}$$

Using Eqs. (46)–(48) in Eq. (44), and substituting (39) for the fertility rate, we finally arrive at the long-run balanced growth rate in the modern growth regime:

$$g_A = \left(\frac{\theta\mu}{1+\beta+\xi}\right)^{\frac{1+\lambda\sigma}{1-\chi}} - 1. \tag{49}$$

From this expression, a number of intuitive results that are in line with the literature (cf. Strulik et al., 2013; Prettner & Werner, 2016; Baldanzi, Bucci, & Prettner, 2021) follow. The preference parameter for education, θ, raises individual human capital accumulation 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. To summarize, this means that fertility and economic growth are inversely related, which implies that the model neither features a strong, nor a weak scale effect. Since both of these scale effects are criticized as counterfactual, the model is better aligned with empirical evidence on the relation between population growth and economic growth in the long run (Brander & Dowrick, 1994; Ahituv, 2001; Herzer, Strulik, & Vollmer, 2012; Strulik et al., 2013; Bucci & Prettner, 2020).

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 the effects discussed so far 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.*

Again, the results of this proposition are consistent with the empirical evidence that shows a positive effect of education on long-run economic growth (cf. de la Fuente & Domenéch, 2006; Cohen & Soto, 2007; Baldacci, Clements, Gupta, & Cui, 2008; Hanushek & Woessmann, 2012).

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. *Long-run economic growth increases unambiguously with a faster accumulation of basic scientific knowledge and with a higher degree of transmission from basic scientific knowledge to applied knowledge production as represented by the terms λ and σ, respectively. Thus, basic scientific knowledge is an important driver of economic prosperity in the long run.*

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 both remain crucial in determining economic prosperity in the long run. When it comes to modern economic growth, these ingredients are much more important than population growth, which has even a negative effect on long-run economic prosperity in our setting (see again Brander & Dowrick, 1994; Ahituv, 2001; Herzer et al., 2012; Strulik et al., 2013; Bucci & Prettner, 2020, for the corresponding empirical evidence).

3. Effects of the Scientific Revolution on long-run economic development: numerical analysis

This section is devoted to a simulation of the model with the purpose of illustrating its dynamics. We do not claim that we are able to match the data perfectly, which would be a misguided attempt anyway. The main reason is that our stylized Unified Growth model necessarily abstracts from important aspects that are present in the real world such as mortality, heterogeneity among individuals, institutional changes, changes of beliefs and norms, and exogenous events such as wars. In particular, we acknowledge that the dynamics of the population and of human capital accumulation are not captured well by the simulation of our model. Nevertheless, we think that the simulation is an important exercise because it illustrates that many of the qualitative insights of the model are in line with the observed data.

3.1. Data

In our simulations, we trace the developments of total factor productivity (TFP), basic scientific knowledge, wage income, the net fertility rate, and individual human capital. We compare the output trajectories implied by our model to long term data from the United Kingdom (UK) reaching back before the Industrial Revolution. It is natural to use UK data in this context because it was the forerunner in both the Scientific Revolution and the Industrial Revolution (Galor, 2005; Galor, 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, Campbell, Klein, Overton, and van Leeuwen (2015). Using 25-year 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 1700 onward (Bornmann & Mutz, 2015). Here, we follow the reasoning of Squicciarini and Voigtländer (2015), who have used the number of subscribers to the Encyclopédie of Diderot and d'Alembert as a measure of the presence of knowledge elites in the French population. The Encyclopédie represented the most important collection of scientific and technological knowledge at the time. As explained in Subsection 2.4, basic scientific knowledge is useful for applied research without, however, being patentable, i.e., it is non-rival and nonexcludable. Thus, using patent data as a measure for basic scientific output would be misleading. Still, we are aware that the number of citations is only a crude indicator for basic scientific activity and the environment for it to flourish, but it is the best that we have at our disposal. In addition, more citations surely imply a higher rate of knowledge diffusion and, thus, indicate a more intensive use of basic scientific knowledge 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 rate. As a proxy for this, we refer to the real weekly wage in the UK from 1760–2000 as reported by Our World in Data (2022). This series is by and large consistent with the real wage of UK craftsmen during 1700–2000 as reported by Clark (2005).

In our model, fertility is the number of children per 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 & 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, Lindgren, Johansson, and Rosling (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 net fertility rate per person as used in our model. The data cover the period 1800–2000.

Finally, human capital is one of the driving forces of the transition to sustained economic development. We use the time series on mean years of schooling in the UK from Madsen and Murtin (2017) and apply a Mincer equation to transform the education data from 1700–2000 into units of human capital. For this purpose, we use the average of the estimated coefficients of the return to schooling in the UK as reported by Psacharopoulos and Patrinos (2018) in their review of Mincer equation estimates. With this procedure of calculating individual human capital, we follow standard economic practice (Hall & Jones, 1999; Prettner, Bloom, & Strulik, 2013; Tamura, Dwyer, Devereux, & Baier, 2019; Bloom, Canning, Kotschy, Prettner, & Schüneman, 2022).[15]

3.2. Simulation results

For our simulation, we have data covering up to 300 years and assume that a generation lasts for 30 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 $\alpha = 0.33$, which is in line with the literature (Jones, 1995; Acemoglu, 2009). We set the time costs for raising one child to 5.8%, i.e., $\psi = 0.058$. Assuming that the available time per day net of sleep is equal to 16 hours, this would amount to a bit less than one hour per day. As such, it is reasonably in line with the data on time use per child as reported by Sani et al. (2016, Table 1). The yearly individual discount rate is approximately 2%, which corresponds to a discount factor of $\beta = 0.55$ over 30 years (Cropper, Freeman, Groom, & Pizer, 2014). All other parameter values are chosen to resemble the data as precisely as possible and are summarized in Table 1.[16] The initial values for productivity, basic scientific knowledge, and the size of the workforce are taken as $A_0 = 10, B_0 = 15$, and $L_0 = 5$.

Fig. 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 1880. Broadly consistent with existing works, TFP is stagnant for decades until the mid-nineteenth century, when the Industrial Revolution altered production possibilities in a fundamental way (Galor & Weil, 2000; Galor, 2005; Galor, 2011; Mokyr, 2005; Strulik et al., 2013). Thus, our predicted TFP series matches the onset of the Industrial Revolution. In addition, the model predicts the long-run growth rate and the long-run level of TFP at the end of the twentieth century well in line with the data.

Which dynamics pave the way to sustained economic development? Before the onset of the Industrial Revolution, wage income is low. Accordingly, education 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 is low and the stock of basic scientific knowledge is small, as is the stock of aggregate human capital. Scientists in the applied research sector would therefore be 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 the decrease in the marginal productivity of human capital in the final goods sector and a slow increase in the stock of basic scientific knowledge that both result from the increasing population size, productivity in the applied research sector rises and becomes high enough for researchers to be increasingly attracted from final goods production to applied R&D. This is the time when productivity levels start to rise.

Additional insights are obtained from Fig. 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 innovation-driven TFP growth may have decreased, which could explain why the model predicts TFP growth in line with the data but a lower rate of increase in the stock of basic scientific knowledge than we observe. A second reason for the discrepancy of the model predictions and the data could be that we are only able to measure TFP and the stock of basic scientific knowledge imperfectly.

Wage income is depicted in Fig. 3 and is also normalized to unity in 1880. As for TFP, we predict the takeoff approximately right. After the takeoff, we first overestimate the growth rate slightly, whereas we underestimate it in the late twentieth century. The main reason for this is the fact that our model does not account for structural change and the move of labor from agriculture to manufacturing. The flow of labor from agriculture to manufacturing was an important force that kept wage growth subdued in the early phase of the Industrial Revolution. Once the flow ebbed, wages started to rise much faster in manufacturing and therefore in the data.

Fig. 4 displays the dynamics of fertility in the model and in the data. The predicted fertility rate is initially high and constant. Then, at the beginning of the demographic transition, it increases for one generation, after which it starts to decline sharply due to increasing education investment that is instigated by income growth and the associated quantity-quality tradeoff effect. Comparing the model outcome to UK data, a similar trend can be observed. Importantly, the fertility rate is high for low income levels and it decreases below replacement fertility at the end of the twentieth century. Overall, the model captures the demographic transition reasonably well.

Finally, inspecting Fig. 5, individual human capital in the data and in the model behave similarly until the Industrial Revolution, after which an increase in the growth rate can be observed in the data but an even faster increase in the prediction of the model. While the model predicts a slowdown of the accumulation of human capital in the second half of the twentieth century — reflected by the fact that the blue solid line is concave — this slowdown cannot be observed in the data. At the end of the time horizon in 2000 and in terms of the level of human capital, the model prediction and the data are, however, reasonably close to each other.

3.3. Comparative dynamics

So far we have shown the importance of the Scientific Revolution for long-run economic development 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 development by employing a comparative dynamics 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 Fig. 6, we show the evolution of wages given different assumptions on the productivity of thinkers in basic science. With the exceptions of γ and B_0, all parameter values and initial condi-

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[15] For further works on the relationships among education, human capital formation, and economic growth, see (Hanushek & Kimko, 2000; Hanushek & Woessmann, 2012; Hanushek & Woessmann, 2012).

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

Table 1
Parameter values for the simulation.

Parameter	Value	Parameter	Value	Parameter	Value
β	0.55	η	0.1	χ	0.425
ξ	0.35	μ	4.5	σ	0.13
θ	0.24	$\bar{r}$	0.88	λ	0.95
ψ	0.058	δ	0.77	γ	0.5
$\bar{e}$	0.5	κ	1.9	$\bar{c}$	0.5
α	0.33				

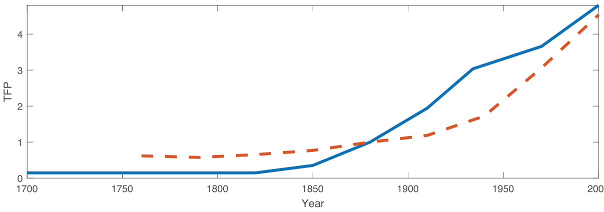

Fig. 1. Evolution of TFP (model prediction: solid blue line; data: dashed red line).

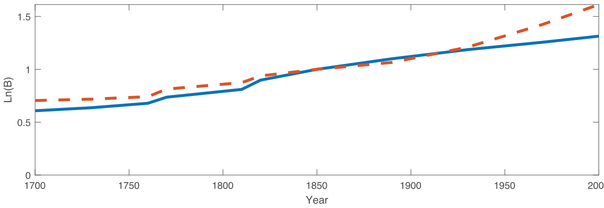

Fig. 2. Logarithm of the stock of basic scientific knowledge (model prediction: solid blue line; data: dashed red line).

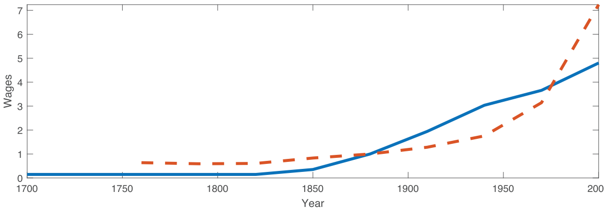

Fig. 3. Evolution of wages (model prediction: solid blue line; data: dashed red line).

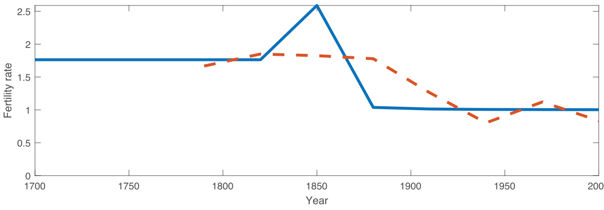

Fig. 4. Evolution of fertility (model prediction: solid blue line; data: dashed red line).

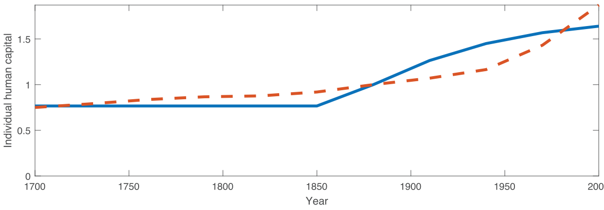

Fig. 5. Individual human capital (model prediction: solid blue line; data: dashed red line).

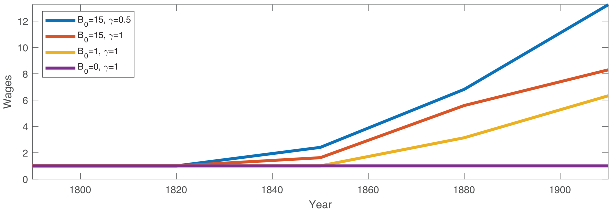

Fig. 6. Wages for different values of γ and initial levels of B_0.

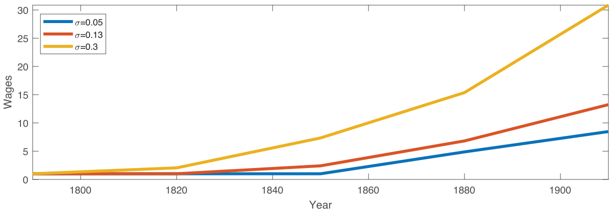

Fig. 7. Wages for different values of σ.

tions are as in Subsection 3.2. The result of the baseline combination of $\gamma = 0.5$ and $B_0 = 15$ is displayed as the blue line. By varying γ and B_0, we get different scenarios of the accumulation of basic scientific knowledge, which, in turn, affects the productivity of scientists working in applied R&D and, thus, economic progress. As we will see, in the case of an extreme restriction of basic science below the threshold level $\overline{B}$, a takeoff to sustained development would not occur at all.

We observe in Fig. 6 that the rate of economic growth decreases with γ such that the takeoff to long-run economic development is less steep (see the red line for the case of $\gamma = 1$ and $B_0 = 15$). The intuitive explanation is that a low γ implies a more “enlightened society” in which new ideas are more likely to be accepted and used in productive knowledge creation. Therefore, the profitability of applied research increases at a faster pace. By contrast, the Industrial Revolution is hampered as γ increases. In the extreme case of $\gamma = 1, B$ remains constant at the initial level. In this case, the takeoff may be delayed by one generation (as shown by the yellow line for $\gamma = 1$ and $B_0 = 1$). Since the productivity of scientists in the applied research sector is determined not solely by scientific knowledge but also by education (human capital), the economy still reaches the threshold at which applied research becomes profitable. Eventually, better educated applied scientists are able to compensate the lack of growth in basic scientific knowledge and the Industrial Revolution can still take its course. However, the setback of one generation (or 30 years) is substantial in its own right. In addition, in a situation with a constant level of B, the economic growth rate after the takeoff is substantially lower than in the case of a growing B. Since small differences in growth rates accumulate to large differences in long-run income levels over centuries, these results emphasize the crucial importance of basic scientific knowledge accumulation for long-run economic prosperity.

Changing, *ceteris paribus*, the intersectoral spillovers, σ, also affects long-run economic development and wages with the intuition following a similar logic as in the case of changes in γ. Fig. 7 displays the results of such an exercise and shows that the timing of the takeoff crucially hinges on the degree of transmission of basic scientific knowledge into applied knowledge production. For low spillovers, i.e., if the transmission of basic scientific knowledge 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 high pace of basic scientific discoveries but these discoveries are not considered in applied research, the productivity in—and the profitability of—developing new blueprints is low, which delays the takeoff. These observations together with the observations above lead to the following remark.

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.

What happens if already the initial level of basic scientific knowledge is below the threshold level needed for long-run economic development such that not only g_B were zero but also B_0? Such a scenario is illustrated by the violet line in Fig. 6. The economy would not take off at all because without a solid enough understanding of the laws of nature and of scientific inquiry, no productive R&D is possible, leaving the economy stagnant indefinitely. This fits well to the historical observation that literacy and education levels of the population alone are not sufficient predictors for economic growth. It is the combination of the Scientific Revolution and the overall level of education that is required in order to take off. We are thus able to state the following remark.

Remark 2. A sufficient amount of basic scientific knowledge is indispensable for an economy to take off because productive applied R&D requires at least a basic understanding of the laws of nature and of scientific inquiry.

The results described in Remarks 1 and 2 have the potential to explain why in countries in which scientific inquiry is severely constrained—for example, due to religious or cultural reasons or due to oppressive rulers—the takeoff to sustained economic development is delayed severely or may not occur at all. As such, our framework has the potential to explain why the Industrial Revolution occurred first in the UK, which was also a forerunner in the Scientific Revolution. China may be a good example that a high level of human capital does not necessarily translate into a takeoff to modern economic growth in the absence of basic scientific knowledge or an environment that fosters scientific inquiry (see Baten, Ma, Morgan, & Wang, 2010, p. 357). Another example is Scandinavia, which was already fully literate in 1800, but an industrial latecomer (Broadberry & O'Rourke, 2010, pp. 30).

That our framework is able to explain such *reversals of fortune* (Acemoglu, Johnson, & Robinson, 2002) is further illustrated in Table 2. Here, we show the ratios of basic scientific knowledge, applied knowledge, and of wages for two countries 1 and 2 for the years 1700 and 1850. Thereby we assume that country 1 exhibits the same parameter values and initial conditions that we assumed above for the UK, while country 2 starts with an initial advantage but less favorable settings for the creation of basic scientific knowledge. In particular, we assume that country 2 has 5% higher stocks of A and B in the year 1700, which translates into a wage that is also approximately 5% higher than in country 1. However, the basic science sector in country 2 is characterized by $\gamma = 0.99$ and $\sigma = 0.01$, i.e., a severely restricted accumulation of basic scientific knowledge.

We observe that country 2 is more developed in the year 1700 but country 1 exhibits a *Culture of Growth* which leads to an earlier and stronger takeoff compared to country 2. At the end of our period under consideration, country 1 not only exhibits a substantially greater stock of basic scientific knowledge but, even more importantly, has overtaken country 2 in terms of economic development. Within a comparatively short period of time, fortune has reversed.

Table 2
Illustration of a reversal of fortune.

Outcome variable	Initial ratio in 1700	Ratio in 1850
B_2/B_1	1.05	0.30
A_2/A_1	1.05	0.44
w_2/w_1	1.05	0.44

4. Conclusions

We propose a novel Unified Growth model that sheds light on the role of the Scientific Revolution in the transition to sustained innovation-driven economic development. 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 are crucial drivers of economic progress. If the stock of basic scientific knowledge does not grow or if the transmission of scientific achievements to applied research is limited, the takeoff to sustained economic development will be delayed severely. In the extreme case in which scientific inquiry is prevented altogether, e.g., for religious reasons or by oppressive rulers, the takeoff to sustained economic development may not occur at all. The policy implication that emanates from our analysis is clear: if governments care about the long-run well-being of the population, they should foster basic scientific inquiry.

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.

Of course, we acknowledge that the stylized framework we proposed cannot explain all aspects of economic development and does not always match the observed data series to our full satisfaction. This is mainly due to the fact that such a theoretical framework can never incorporate all aspects that are important for development. In particular, we abstracted from structural change as another important driver of economic transitions, from cultural change in the sense of changing norms and secularization, and from institutional changes other than those related to basic science to mention only the most obvious ones. Including such aspects may be an interesting and challenging area of further research. As the final goal it would be fascinating to disentangle the extent to which social aspects, institutional change, and knowledge creation (both in the form of education and of scientific progress) interacted in the emergence of the *Culture of Growth*.

CRediT authorship contribution statement

Sibylle Lehmann-Hasemeyer: Investigation, Writing - original draft, Writing - review & editing. **Klaus Prettner:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing. **Paul Tscheuschner:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing.

Data availability

Data will be made available on request.

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Declarations of interest

None.

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