Public Health Investments and the Direction of Technological Progress: a Theory of Deskilling during the British Industrial Revolution

Tanguy Le Fur*

September 2019 - Preliminary draft

Abstract

The British Industrial Revolution was initially characterized by a decline in the average level of skills of workers, as technological progress was unskill-biased and life expectancy stagnated despite output growth. In this paper, I rationalize these features of development in a growth model in which the skill composition of the labor force and the direction of technological progress interact, and public health investments are the result of profit-maximization of the capitalist class. I show that improvements in workers' longevity can generate a switch from unskill- to skill-biased technological progress. However, unskill-biased technological change reduces the incentives of the capitalist class to undertake public health investments and therefore delays the take-off to a regime of sustained economic growth. The simulation of the model economy replicates the episode of deskilling experienced during the industrialization process in England between 1720 and 1870.

Keywords: Directed Technological Change, Deskilling, Public Health, Unified Growth Theory

*Aix-Marseille University, CNRS, EHESS, Centrale Marseille, AMSE − email: tanguy.le-fur@etu.univ-amu.fr.
I thank Ryo Horii and Raouf Boucekkine for lengthy and enthusiastic conversations on an earlier version of the draft, as well as Kevin Genna and Armel Ngami for helpful insights. This paper has benefited from discussions with Luca Pensieroso, Alain Trannoy, Gregory Ponthiere, Cecilia Garcia-Penalosa and participants of the AMSE PhD seminar.

1 Introduction

Improvements in life expectancy, by increasing the time-horizon over which individuals may reap the fruits of educational investments, are often considered a necessary condition to the accumulation of human capital and the take-off to a regime of sustained economic growth (Boucekkine et al, 2003; Soares, 2005; Cervellati & Sunde, 2005). However, looking at the British Industrial Revolution calls for a more nuanced view. Life expectancy actually stagnated at the time England experienced an unprecedented boom in economic growth, and increased only after substantial public investments in health-related infrastructure were made in the late 19th century. Furthermore, economic historians have argued that the average level of human capital of the labor force actually declined over the period and that its role in the industrialization process was only minor[1].

In this paper, I study how the direction of technological progress influences the incentives to undertake public health investments. In particular, I investigate how *unskill-biased* technological progress, by reducing the role played by human capital in production, may have reduced the motives of British capitalists to raise taxes on their own wealth to finance improvements in longevity for the working class. I propose a theory that rationalizes features of the British Industrial Revolution: the first stage of development is characterized by a stagnation in life expectancy as well as a decline in the share of skilled workers – an episode of deskilling. Public health investments occur only when the returns to human capital become greater to those of physical capital as profit-maximizing capitalists find it beneficial to entice workers to invest in education. Feedback loops between the skill composition of the population and the direction of technological innovations then generate an endogenous switch from unskill- to skill-biased technological progress and a take-off to a regime of sustained economic growth.

The central feature of the model is that political power is detained by the elite capitalist class. Capitalists therefore set the rate at which their own wealth is taxed to finance public investments in health infrastructure. Two characteristics of the institutional framework of England at the time motivate this. First, public health investments had to be locally financed via heavy property taxes. The burden of their cost was therefore not equally shared between social classes: it fell exclusively on upper- and middle-class landlords, entrepreneurs and capitalists. The working class thus did not participate to their funding. Furthermore, it was also excluded from the political process through which such

[1] See Nicholas & Nicholas (1992) and Clark (2005) for examples.

taxes were agreed upon. Indeed, the franchise allowing *men* to vote in local elections at the time was confined to those duly paying this property tax. England was in practice a 'taxpayer democracy'.[2] Therefore, only those bearing the cost of public health investments were allowed to participate in the decision to levy taxes to finance them. Importantly, they were also those who would benefit the less from them: Szreter (2002) describes how the propertied classes escaped the insanitary conditions of the urban centers by physically moving away to more salubrious areas, resulting in drastic health inequalities between the bourgeoisie and the proletariat well documented by de la Croix & Sommacal (2009). For the sake of simplicity, I assume that capitalists already enjoy a substantial health advantage over workers and that they do not directly benefit from public health measures they decide to take, but only indirectly via their effects on both workers' productivity and education level.

I therefore build a model in which public health investments are the result of profit-maximization by the capitalist class. This paper thus emphasizes that the study of long-run economic development should not ignore institutional and political dynamics. Power relations between groups of individuals may shape aggregate economic outcomes and are often crucial to understand the growth path an economy engages in. It is therefore necessary to investigate economic incentives in terms of social classes, and especially how the rational decisions of the class holding the political power influence the actions of other actors of society. This is the matter of the vast literature on the political economic of growth that studies the provision of public goods, the redistribution of resources, or the extension of the franchise by the elite,[3] but the closest paper to this one is Galor & Moav (2006). Focusing on the provision of education in industrializing England, they argue that capitalists were willing to fund public schooling through wealth taxation because they directly benefited from the accumulation of human capital by workers. The mechanism through which public investments are decided is therefore the same as in this paper.

I nevertheless depart from Galor & Moav (2006) in two ways. First, I consider public investments in health-related amenities rather than education. While capitalists' willingness to provide public health stems from the incentives it gives to workers to invest in their education, the inequality in life expectancy between capitalists and workers makes the latter benefit disproportionally from such investments. This implies that, had workers

[2]See Aidt, Daunton & Dutta (2010) for an extensive discussion of the institutional background of mid-Victorian cities.

[3]Notable examples are Acemoglu & Robinson (2001), Bourguignon & Verdier (2000) and Eicher et al (2009).

possessed political power during the Industrial Revolution, investments in public health would probably have occurred much earlier. In Galor & Moav (2006) on the contrary, workers and capitalists demand the same level of wealth taxation and there is no conflict on the funding of public schooling. Second, their theory relies on a strong complementarity between skills and physical capital, characterized by a production function where human capital gradually gains importance with the accumulation of physical capital. However, as documented in the next section, the role played by the skills of workers in aggregate production did not follow such a monotonous evolution over the course of development. I therefore go further by allowing technological progress to be biased toward unskilled rather than skilled labor. I show how, by reducing the prominence of skills in aggregate production, unskill-biased technological progress negatively affects capitalists' incentives to undertake public health investments that would raise the returns to education for workers.

To endogeneize the direction of technological progress, I consider two sectors employing respectively skilled and unskilled labor and assume that their relative weight in aggregate production is a function of the skill composition of the labor force. The productivity of the skilled (unskilled) sector depends positively on the number of skilled (unskilled) workers. This reduced form assumption aims at capturing market size effects driving innovators to direct their efforts towards the sector using the abundant factor.[4] Although attempts to consider the direction of technological progress in long-run growth literature are still scarce, the same intuition lies at the heart of O'Rourke et al (2013). They embed a Schumpeterian innovation sector into a unified growth model and show that technological progress may be unskill-biased in the first stages of development if unskilled labor is the abundant factor, because of such market size effects. Despite their analysis of how individuals' fertility and educational decisions are affected by the direction of technological progress however, they do not consider the provision of public goods such as education or health infrastructure.

The interplay between the skill composition of the labor force and the direction of technological progress is the crux of the theory proposed here. The direction of innovation influences workers' incentives to acquire education, which in turn affect the direction of technological progress, giving birth to feedback loops between the two. The level of life expectancy is crucial for the dynamics of the skills of the labor force. If it is high enough,

[4]See Acemoglu (2002) for a theoretical discussion of how market forces may shape the direction of technological progress.

the share of unskilled workers decreases, technological progress is thus skill-biased and the skilled-labor-using sector grows, providing further educational incentives to workers. The economy then converges to a steady state where every worker is skilled. However, if life expectancy is initially low, the economy may instead experience an increase in the number of unskilled workers in the first stage of development. The decline of skills in the labor force directs technology towards to the unskilled-labor using sector, reinforcing the deskilling process until the economy get stuck in a steady state where every worker is unskilled.

Improvements in life expectancy can therefore generate a switch from unskill- to skill-biased technological progress and put a halt on the deskilling process by providing workers with incentives to invest in education. However, unskill-biased technological progress reduces capitalists' incentives to undertake public health investments as the role of skills in aggregate production gradually declines. I thus emphasize how the direction of technological change during the industrialization process in England may have delayed much needed investments in health-related amenities, resulting in the stagnation of the life expectancy of the working class in the most of the 19th century. The accumulation of physical capital being subject to diminishing returns however, the returns to skills nevertheless surpass them at some point, and capitalists agree to set a positive tax rate on their wealth to fund public health measures. The increase in longevity provides incentives for workers to invest in education and reallocate to the skill-using sector. The skill composition of the labor force therefore changes as the share of skilled workers starts to increase. This reverses the direction of technological progress by raising the abundance of skilled labor, which triggers the switch from unskill- to skill-biased technological progress. Positive feedback loops between the average skill level of workers and the direction of technology set in, and the economy takes-off to a regime of sustained economic growth where only skill-intensive production prevails and life expectancy keeps on increasing.

The paper is organized as follow: Section 2 provides empirical evidence about the life expectancy and the direction of technological progress during the British Industrial Revolution that motivate the analysis. Section 3 sets up the model. Section 4 investigates how life expectancy, the skill composition of the labor force and the direction of technological progress interact. Section 5 endogenizes the provision of public health and describes capitalists' decisions about taxation. Section 6 provides a numerical simulation of the model that replicates features of England industrialization. Section 7 briefly concludes.

2 Empirical motivations

In this section, I provide empirical evidence for the two surprising features of the British Industrial Revolution that motivate the theory: the stagnation of life expectancy and the crucial role of public health investments in improving the condition of the working class, as well the process of deskilling driven by unskill-biased technological progress.

2.1 Life expectancy during the Industrial Revolution in England

In most theoretical growth models about the role of health on human capital accumulation, improvements in health are considered to be a by-product of economic growth. Life expectancy is often assumed to be an increasing function of output or technological progress. The underlying argument is that the rise of standards of living associated to economic development naturally improves population health. This was the message of Thomas McKeown's influential *The Modern Rise of Population* (1976) in which he argues that increasing per capita nutritional intake permitted by higher real incomes was the main factor driving increases in longevity in England and Wales since the mid 19th century.

Taking a closer look at the evolution of life expectancy in England during the Industrial Revolution however casts doubt on the close link between health and income. Wrigley & Schofield in their comprehensive *The Population History of England: 1541–1871* (1981) show how the gradual increase in life expectancy during the 18th century stopped at the beginning of the 19th century. It is striking that, at the time when England was experiencing unprecedented economic growth, life expectancy stagnated and did not improve before the last quarter of the century. Szreter & Mooney (1998) describe an even grimer situation in British cities where negative externalities associated with urbanization exerted a penalty on the health of the population. Life expectancy in England surpassed the levels at the start of the Industrial Revolution only after 1870, as can be seen in Figure 1.

Figure 1. Life expectancy at birth in England in the 19th century

Sources: Szreter & Mooney (1998) for British cities, Wrigley & Schofield (1981) for national average in England and Wales

Steckel (1999) and Steckel & Floud (1997) confirm that population health might actually have decreased during periods of industrialization and urbanization in the first half of the 19th century (with the notable exception of Sweden). Recent empirical evidence would have come as no surprise to acute contemporary observers who already documented the dire living conditions and the immiseration of the working class in industrializing countries. Engels' magnum opus, *The Condition of the Working Class in England* (1845), paints a dark picture of the industrial proletariat at the time. The hardship of new labor, he argued, along with urbanization and the lack of public health infrastructures exerted a serious toll on the health of the working class.

Although it may seem natural to think that economic growth translates into better standards of living and higher life expectancy, Szreter (1997) argues that the growth process itself has disruptive effects on society that may pose threats to population health. Addressing such potentially negative externalities, he claims, *"requires, at a minimum, massive investment in urban preventive health infrastructure, and an accompanying regulatory and inspection system, along with a humane social security system"* (Szreter 2004, p.82). Looking carefully at British history, Easterlin (1999) documents how, rather than economic development and market forces, it is the combination of scientific discoveries and their application through collective action that were the main factors responsible for the take-off of life expectancy in England around 1871. Indeed, big public works such as building sewers and sanitation systems, providing clean water, pasteurizing milks or running mass vaccinations campaigns, coupled to healthy individual behavioral changes greatly encouraged by the government, allowed to curb mortality from infectious diseases and had an unprecedented positive impact on life expectancy – an episode called the sanitation revolution.[5] Furthermore, the prominent role played by public health measures in the improvements of population health is not a British peculiarity: looking at the US, Cutler & Miller (2005) estimate that water purification alone can account for half the mortality decline in the early 20th, a striking figure, and Costa (2015) also emphasizing the role played by scientific advances, highlights how substantial public health measures were necessary to their application. Cutler, Deaton & Lleras-Muney (2006) stress that the importance of public health investments in the rise of life expectancy is proof that *health comes from institutional ability and political willingness to implement known technologies, neither of which is an automatic consequence of rising incomes"* (p.116). One objective of this paper is therefore to break down the direct link between aggregate output and population health that is often assumed in theoretical growth models, and instead study the endogenous provision of public health over the course of development; with a focus on the British experience.

2.2 Deskilling and the direction of technological progress

Although technological progress is commonly seen today as being skill-biased and increasing the relative demand for skilled labor, this view probably stems for our recent experience in the modern world. Classical economists however, from Adam Smith to Karl Marx,[6] viewed technological progress as a process inherently biased towards unskilled workers. Indeed, during the Industrial Revolution, physical capital and unskilled labor substituted for skilled labor with the division of labor, mechanization and the rise of the factory system. In the course of the 18th and 19th centuries, skilled artisans who used to supervise the whole production process gradually disappeared as technological innovations raised the demand for unskilled workers instead – an episode often labeled the workshop-to-factory transition.[7] The complementarity between human and physical capital at the heart of Galor and Moav's theory only emerged around the turn of the 20th

[5]Demographer and sociologist Samuel H. Preston was among the firsts to stress the role of such public health investments in the major improvements in longevity at the end of the 19th and the beginning of the 20th century (Preston 1975, 1976).

[6]See Brugger & Gehrke (2018)

[7]de Pleijt et al (2019) argue it may be more accurate to talk about a framwork-to-factory transition.

century (Goldin & Katz, 1998).

Evidence for this process of *deskilling* and the decline of the role of workers' human capital in production is usually derived from data on educational attainment or literacy rates. Mitch (1993) documents a relatively low performance in terms of literacy during the British Industrial Revolution, with rates fluctuating around 60% between 1750 and 1850, without any significant improvement. Similarly, Nicholas & Nicholas (1992) emphasize how literacy really was an investment in human capital at the time. They show that, while England had attained a sufficient level of literacy on the eve of the Industrial Revolution to allow growth to set in, there was a stagnation and even a decline in male literacy rates in the late 18th and early 19th century, as further measures to decrease illiteracy were deemed unnecessary. They emphasize the unskilled-labor intensive nature of production in the industrialization process of England, and how *"the factory deskilled and proletarianized the work force by destroying old skills, substituting unskilled female and child laborers for skilled make workers, and relying on power-driven machinery which created jobs that required no formal skills or even rudimentary levels of literacy"* (pp.17–18). Further indirect evidence of the unskill-biased nature of technological progress can be found in the work of Jane Humphries (2010, 2012), who documents through qualitative analysis of working men autobiographies the rise in the demand for child labor spurred by mass production at that time. Quantitatively, Kirby (2005) estimates that more than 40% of boys aged 10–14 were employed by the mid 19th century.

Literacy rates however are a very imperfect measure of the level of human capital of the population, as they proxy only primary schooling and therefore do not differentiate a low-skill but literate factory worker from a skilled engineer. In recent work, Alexandra de Pleijt (2018) goes further by studying the evolution of human capital in England as measured in average years of education instead, disentangled into primary, secondary and tertiary schooling. She finds that years of schooling increased substantially from the 16th century onwards, which is consistent with Boucekkine et al (2007) who document a surge in the building of new schools during the period. However, she shows how starting from the early 18th century, years of formal education started to decline, driven by a stagnation in years of primary schooling while secondary and tertiary educational attainment decreased significantly from 1700 to 1880. A direct implication of this evolution is a remarkable increase in the share of unskilled workers in England from the onset of the Industrial Revolution onwards, documented in de Pleijt & Weisdorf (2017). Using occupational titles to classify English workers according to the skills encompassed by their work, they find that the share of unskilled workers was as low as 20% in the 16th century, but that it rose strikingly after 1700 to reach almost 40% in the 19th century. This process of deskilling of the labor force illustrated in Figure 2 is a clear indication that the demand for educated workers fell sharply during the British Industrial Revolution and the objective of this paper is to replicate this feature of development.

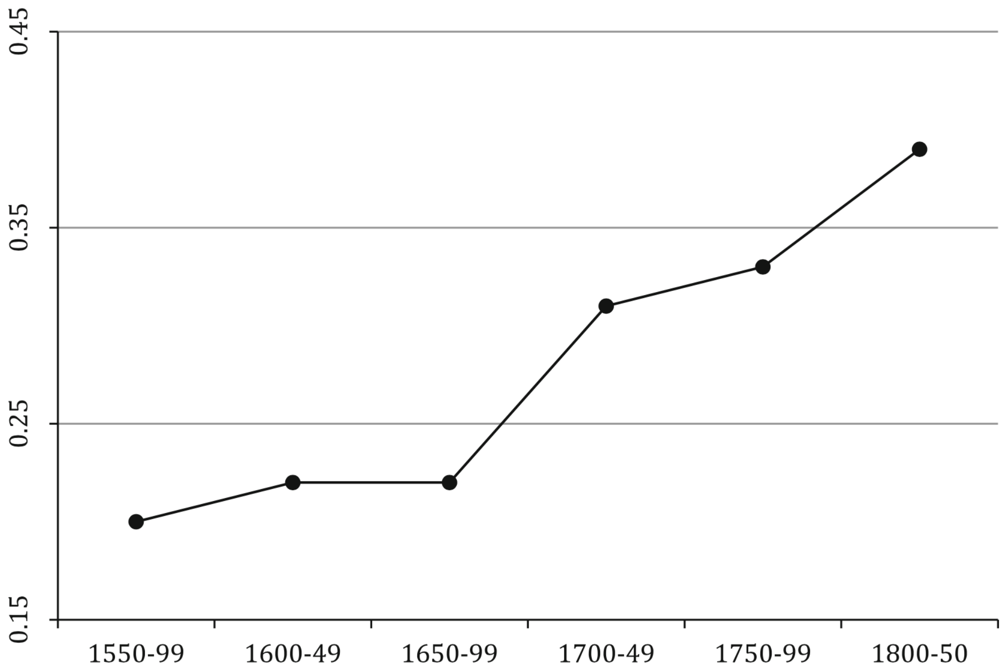

Figure 2. Share of unksilled workers in England: 1550–1850

Sources: de Pleijt & Weisdorf (2017)

It is important to note however that the deskilling hypothesis is not necessarily antagonist to another view of the Industrial Revolution that emphasizes the role of knowledge in the process of industrialisation, by fostering both the invention and the application of new technologies. In the words of Joel Mokyr, the main proponents of this view, *"the essence of the Industrial Revolution was technological, and technology is knowledge"* (Mokyr, 2005; p.19). According to Mokyr & Voth (2009), technological advances were a close collaboration between formally educated scientists trying to understand the nature of the world in the spirit of the Enlightenment, and skilled craftsmen who searched to apply this knowledge to production, driven by profit. Squicciarini & Voigtlander (2015) show that disentangling the 'upper-tail' knowledge of an elite at the top of the skill distribution from that of the average workers reinstates the role of human capital in the Industrial Revolution. It is not in contradiction however with a decline in the average level of skills in workforce, as new innovations may very well have been biased towards unskilled labor, raising the demand for uneducated workers. Mokyr (1990) himself mentions the replacement of skilled artisans replaced by unskilled workers using new and superior technology.

3 The Model

3.1 Production

The economy is composed of two sectors Y^s and Y^u using respectively skilled L^s and unskilled labor L^u, both coupled with capital K. I assume both sector are perfect substitute in the constitution of aggregate output Y, such that:

$$Y_t = z_t \left\{ (1 - x_t) Y_t^u + x_t Y_t^s \right\} \tag{1}$$

Where x_t is the relative productivity of the skilled sector and z_t is Total Factor Productivity (TFP). The production function of each sector is a Cobb-Douglas with the same capital intensity α to make things as tractable as possible. The sector-specific level of technology is constant and denoted by A^j for $j = u, s$.

$$Y_t^u = A^u (K_t^u)^\alpha (L_t^u)^{1-\alpha} \quad ; \quad Y_t^s = A^s (K_t^s)^\alpha (L_t^s)^{1-\alpha}$$

Factors of production are paid their marginal product, therefore:

$$w_t^u = \frac{\partial Y_t}{\partial L_t^u} = z_t (1 - x_t) A^u (1 - \alpha) \left(\frac{K_t^u}{L_t^u} \right)^\alpha \qquad \& \qquad w_t^s = \frac{\partial Y_t}{\partial L_t^s} = z_t x_t A^s (1 - \alpha) \left(\frac{K_t^s}{L_t^s} \right)^\alpha$$

$$r_t^u = \frac{\partial Y_t}{\partial K_t^u} = z_t (1 - x_t) A^u \alpha \left(\frac{K_t^u}{L_t^u} \right)^{\alpha - 1} \qquad \& \qquad r_t^s = \frac{\partial Y_t}{\partial K_t^s} = z_t x_t A^s \alpha \left(\frac{K_t^s}{L_t^s} \right)^{\alpha - 1}$$

Capital is fully mobile across sectors and both interest rates therefore equalize. This gives:

$$\frac{K_t^s / L_t^s}{K_t^u / L_t^u} = \left(\frac{A^s}{A^u} \frac{x_t}{1 - x_t} \right)^{\frac{1}{1-\alpha}} \tag{2}$$

Denoting the fraction of the aggregate capital stock K_t employed in the low-skill sector by γ_t such that $K_t^u = \gamma_t K_t$ and $K_t^u = (1 - \gamma_t) K_t$, the above equation gives:

$$\gamma_t = \frac{(A^u [1 - x_t])^{\frac{1}{1-\alpha}} L_t^u}{(A^u [1 - x_t])^{\frac{1}{1-\alpha}} L_t^u + (A^s x_t)^{\frac{1}{1-\alpha}} L_t^s} \quad \& \quad 1 - \gamma_t = \frac{(A^s x_t)^{\frac{1}{1-\alpha}} L_t^s}{(A^u [1 - x_t])^{\frac{1}{1-\alpha}} L_t^u + (A^s x_t)^{\frac{1}{1-\alpha}} L_t^s}$$

Let us rewrite the production function as follow:

$$Y_t = z_t K_t^{\alpha} \left\{ (A^u[1 - x_t])^{\frac{1}{1-\alpha}} L_t^u + (A^s x_t)^{\frac{1}{1-\alpha}} L_t^s \right\}^{1-\alpha} \tag{3}$$

The skill premium can be expressed as a function of sectoral productivity levels:

$$\omega_t \equiv \frac{w_t^s}{w_t^u} = \left(\frac{A^s}{A^u} \frac{x_t}{1 - x_t} \right)^{\frac{1}{1-\alpha}} \tag{4}$$

3.1.1 The direction of technological progress

To model the direction of technological progress, I draw inspiration from several papers. First, Cervellati & Sunde (2015) interpret the increase of the relative weight of the skill-intensive sector in aggregate production x_t as *skill-biased technical change*. A feature of their model however is that the relative productivity of the skilled sector can only grow, which leaves no room to the matter of interest here, *unskill-biased technological progress*. In this paper, I therefore consider that sectoral relative productivities can go in either directions, and technological change is said to be skill-biased when x increases, and unskill-biased when x decreases. What then determines in which sector innovation occurs? I follow the basic intuition underlying the canonical directed technical change model (Acemoglu, 2002) in which innovators decide upon the amount of research and development in a given sector according to profit incentives. Two countervailing forces influence the direction of technological progress: a price effect encouraging innovation of more expensive goods produced using scarce factors and a market size effect that fosters innovation in the technology using the abundant factors. It is the elasticity of substitution between the factors that ultimately determines which effect dominates. O'Rourke et al (2013) embed such an innovation process in which profit-maximizing innovators decide in which sector to innovate in a unified growth model. They argue that, given that skilled and unskilled labor are grossly substitutable, innovation was directed towards the unskilled-labor-using sector in the first stage of the Industrial Revolution because of the market-size effect. In this paper, I do not explicitly model the innovation sector. Instead, I make the reduced form assumption that the relative productivity of each sector is a function of the contemporary skill composition of the labor force. Specifically, I assume that the weight in aggregate production of the skilled (unskilled) sector is a decreasing (increasing) and linear function of the share of unskilled workers $\mu_t = \frac{L_t^u}{L_t^u + L_t^s}$. Formally:

$$x_t \equiv x(\mu_t) = 1 - \mu_t$$

Furthermore, I assume that the growth rate of TFP is positively affected by the number of skilled workers in the previous period. This captures the process of accumulation of *upper-tail* knowledge driven by an elite at the top of the skills distribution described by Mokyr (2005). Cervellati & Sunde make a similar assumption, interpreting the share of skilled workers $(1 - \mu_t)$ as the amount of labor involved in research.

$$g_t^z = \frac{z_{t+1} - z_t}{z_t} = \eta(1 - \mu_{t-1}) \quad ; \quad \eta > 0$$

3.2 Individuals

There are two types of individuals in the economy: workers and capitalists. Both have different objective functions and constraints. I describe each of them in the next subsections.

3.2.1 Workers

Each period, a continuum of workers with unit mass $L = 1$ is born. Each worker lives with certainty through the first period of her life – childhood – and survives with a probability $\phi \in (0, 1)$ to the second period – adulthood. Two things are worth noting. First, I do not consider fertility decisions and instead assume that the number of children born each period is exogenous and constant. Second, the survival probability ϕ enters workers' utility function by multiplying utility in adulthood, effectively acting as a discount factor. Since an individual is expected to live for $1 + \phi$ periods, it is common in the theoretical literature on studying the links between health and growth to interpret ϕ as longevity (Chakraborty, 2004, Raffin & Seegmuller, 2014; de la Croix & Sommacal, 2009). In this paper, I therefore refer to ϕ as life expectancy.

In the first period, workers decide whether to make an indivisible investment in education which is costly in effort. Children are heterogenous in ability, and therefore face a different cost of education accordingly. In the second period of their life, workers who made the educational investment are employed in the skilled sector, while those who did not work in the unskilled sector. They provide inelastically one unit of labor at the prevailing wage in the sector they are employed in and consume the whole of their resulting labor income.[8]

[8] The consumption of a child is implicitly contained in that of her parent.

Lifetime utility for a worker with ability i is of the following form:

$$U_i = -\Delta^i E_t^i + \phi \log c_{t+1}^w \tag{5}$$

Where Δ^i is the effort worker i needs to put in if he undertakes education, hence the lower Δ^i, the more able she is (Δ^i could therefore be interpreted as the inverse of a worker's capacity). E_t^i represents the indivisible investment and takes a value of one if she decides to go to school, and zero otherwise. The budget constraint of any worker is simply:

$$c_{t+1}^w \leq \begin{cases} w_{t+1}^u & \text{iff} \quad E_t^i = 0 \\ w_{t+1}^s & \text{iff} \quad E_t^i = 1 \end{cases} \tag{6}$$

A worker with 'disability' Δ^i therefore decides to invest in education if and only if it increases her lifetime utility. Formally, if $U_i(E_t^i = 1) \geq U_i(E_t^i = 0)$. When taking such a decision, each worker therefore compares the wage differential between the two sectors to his educational effort cost. However, since workers do not observe the future level of wages as it depends on the skill composition of the labor force the next period, I assume that they base their expectations on the current skill premium ω_t. This defines a threshold level $\Delta^\star$ for ability at which $U_i(E_t^i = 1) = U_i(E_t^i = 0)$:

$$\Delta_t^\star = \phi \log(\omega_t) \tag{7}$$

3.2.2 Capitalists

Each period, a number N^k of identical capitalists are born. For simplicity, let us normalize N^k to one. They receive bequests from their parents b_t in the first period. The whole of those bequests is saved. In the second period, they do not work and use their rental income to consume c_{t+1} and leave bequests b_{t+1} to their children in turn. They face a probability of surviving to the second period ϕ^k which is greater than that of workers ϕ.[9] I assume:

$$\phi^k = 1 > \phi$$

The assumption that capitalists already enjoy perfect health will be useful later. It implies that they will benefit from public health measures only via their effects on production, hence on their income. This will simplify the analysis when decisions about the provision of public health are introduced in Section 4. Capitalists derive utility from both consump-

[9]de la Croix & Sommacal (2009) document the substantial health inequalities between the bourgeoisie and the proletariat in England during the Industrial Revolution.

tion and the bequest they leave to their children. They therefore choose c_{t+1} and b_{t+1} to maximize their utility subject to their budget constraint:

$$\max_{c_{t+1};b_{t+1}} U_k = (1-\beta)\log c^k_{t+1} + \beta \log b^k_{t+1} \tag{8}$$

$$s.t. \quad c^k_{t+1} + b^k_{t+1} \leq b^k_t r_{t+1} \equiv I^k_{t+1} \tag{9}$$

Where I^k_{t+1} is capitalists' total wealth. This simply gives:

$$c^k_{t+1} = (1-\beta) I^k_{t+1} \quad ; \quad b^k_{t+1} = \beta I^k_{t+1}$$

3.3 Physical capital accumulation

Capitalists are the only individuals who save. As mentioned above, their savings are equal to the bequest they receive from their parents. Denoting aggregate bequest by $B_t = b^k_t$ and assuming full depreciation for simplicity, the aggregate stock of capital in $t+1$ is therefore:

$$K_{t+1} = B_t \tag{10}$$

4 The distribution of skills in the workforce

I assume that workers' ability $\Delta \in (0;\bar{\Delta})$ follows a uniform distribution with a probability density function $g(\Delta)$. Recall that a child undertakes the indivisible effort investment in education if and only if her ability is lower than the threshold $\Delta^\star_t = \phi \log(\omega_t)$. The threshold is therefore a function of workers' life expectancy and the skill premium: $\Delta^\star_t \equiv \Delta^\star(\phi, \omega_t)$. Let us drop the time subscript and refer to it as $\Delta^\star$ for clarity.

4.1 The share of unskilled workers

In $t+1$, the share of unskilled workers born in t is:

$$\mu_{t+1} \equiv \int_{\Delta^\star}^{\bar{\Delta}} g(\Delta) d\Delta = 1 - G(\Delta^\star) \tag{11}$$

Where $G(\Delta^\star)$ is the cumulative distribution function:

$$G(\Delta^\star) = \begin{cases} 0 \quad \text{for} \quad \Delta^\star < 0 \\ \Delta^\star / \bar{\Delta} \quad \text{for} \quad 0 < \Delta^\star \leq \bar{\Delta} \\ 1 \quad \text{for} \quad \Delta^\star \geq \bar{\Delta} \end{cases}$$

It follows that the share of unskilled workers is equal to 0 when $\Delta^\star \geq \bar{\Delta}$. It is straightforward to show that this is the case for:

$$\mu_t \leq \frac{A}{e^{(1-\alpha)\bar{\Delta}/\phi} + A} \equiv \underline{\mu}$$

Where $A = A^s/A^u$. Conversely, this share is equal to 1 when $\Delta^\star < 0$, hence when:

$$\mu_t > \frac{A}{1+A} \equiv \overline{\mu}$$

Since $\underline{\mu} < \overline{\mu}$ that the total share of unskilled workers in $t+1$ is defined by the following function:

$$\mu_{t+1} \equiv \Lambda(\omega_{t+1}, \phi) = \begin{cases} 0 & \text{for} \quad \mu_t \leq \underline{\mu} < \overline{\mu} \\ \int_{\Delta^\star}^{\bar{\Delta}} g(\Delta) d\Delta & \text{for} \quad \underline{\mu} < \mu_t \leq \overline{\mu} \\ 1 & \text{for} \quad \underline{\mu} < \overline{\mu} < \mu_t \end{cases} \tag{12}$$

The share of unskilled workers is therefore constant for $\mu_t \leq \underline{\mu}$ and $\mu_t > \overline{\mu}$. Partial derivatives for $\mu_t \in]\underline{\mu}; \overline{\mu}]$ are as follow:

$$\begin{aligned} \frac{\partial \Lambda(.)}{\partial \phi} &= -\frac{1}{\bar{\Delta}} \log(\omega_{t+1}) < 0 \\ \frac{\partial \Lambda(.)}{\partial \omega_{t+1}} &= -\frac{\phi}{\bar{\Delta}} \frac{1}{\omega_{t+1}} < 0 \end{aligned}$$

Improvements in life expectancy therefore reduce the share of unskilled workers by lengthening the horizon over which individuals benefit from the educational investment undertaken when young. This is the standard Ben-Porath mechanism that is common in the theoretical literature on health and economic growth. The skill-premium also raises the returns to education, it is therefore natural that it increases the average level of skills of the population.

4.2 Dynamics

Recall that the relative productivities of each sector directly depend on the skill composition of the workforce. The current skill premium on which individuals base their expectations can therefore be expressed as a function of the share of unskilled workers: $\omega_t = \{A \cdot (1-\mu_t)/\mu_t\}^{\frac{1}{1-\alpha}}$. This makes $\mu_{t+1} = \Lambda(\mu_t, \phi)$ an autonomous, first-order, non-linear differential equation, *conditional on* ϕ. In this section, I study the dynamics of the skill composition of the workforce and investigate how it crucially depends on workers' life expectancy ϕ. To this purpose, I explicitly treat ϕ as an argument of the function Λ, which allows for a better exposition. Let us express the share of unskilled workers in $t+1$ as a function of that in the previous period and life expectancy:

$$\mu_{t+1} \equiv \Lambda(\mu_t, \phi) = \begin{cases} 0 & \text{for} \quad \mu_t \leq \underline{\mu} < \overline{\mu} \\ 1 - \frac{\phi}{(1-\alpha)\bar{\Delta}} \log\left(A \cdot \frac{1-\mu_t}{\mu_t}\right) & \text{for} \quad \underline{\mu} < \mu_t \leq \overline{\mu} \\ 1 & \text{for} \quad \underline{\mu} < \overline{\mu} < \mu_t \end{cases} \tag{13}$$

As a first step, let us study the dynamics of μ_{t+1} conditional on life expectancy, that is, for a given ϕ.

$$\frac{\partial \Lambda(.)}{\partial \mu_t} = \begin{cases} 0 & \text{for} \quad \mu_t \leq \underline{\mu} < \overline{\mu} \\ \frac{\phi}{(1-\alpha)\bar{\Delta}} \frac{1}{(1-\mu_t)\mu_t} > 0 & \text{for} \quad \underline{\mu} < \mu_t \leq \overline{\mu} \\ 0 & \text{for} \quad \underline{\mu} < \overline{\mu} < \mu_t \end{cases}$$

The share of unskilled workers in the current period is an increasing function of that of the previous period. This comes from the interplay between the skill composition of the labor force and the direction of technological progress: the greater the current share of unskilled workers, the more technology becomes biased towards unskilled labor which in turn reduces incentives to invest in education and thereby increases the future share of unskilled workers.

$$\frac{\partial^2 \Lambda(.)}{\partial \mu_t^2} = \begin{cases} 0 & \text{for} \quad \mu_t \leq \underline{\mu} < \overline{\mu} \\ \frac{\phi}{(1-\alpha)\bar{\Delta}} \frac{2\mu_t - 1}{(1-\mu_t)^2 \mu_t^2} & \text{for} \quad \underline{\mu} < \mu_t \leq \overline{\mu} \\ 0 & \text{for} \quad \underline{\mu} < \overline{\mu} < \mu_t \end{cases}$$

It is possible to show that on the interval $]\underline{\mu}; \overline{\mu}]$, $\partial^2 \Lambda(.)/\partial \mu_t^2 < 0$ for $\mu_t < 1/2$, $\partial^2 \Lambda(.)/\partial \mu_t^2 = 0$ for $\mu_t = 1/2$ and $\partial^2 \Lambda(.)/\partial \mu_t^2 > 0$ for $\mu_t > 1/2$. $\mu_t = 1/2$ is therefore a unique inflexion point. The study of the function Λ leads to the following proposition:

Proposition 1. *If $A < e^2$,*

(i) There exists two stable steady states $\mu_0^\star = 0$ and $\mu_1^\star = 1$ and a unique unstable steady state $\mu_u^\star \in]\underline{\mu}; \overline{\mu}]$.

(ii) Over time, the share of unskilled workers increases if $\mu_t > \mu_u^\star$ and decreases if $\mu_t < \mu_u^\star$.

(iii) $\mu_u^\star$ increases with workers' life expectancy ϕ.

This proposition describes the evolution of the share of unskilled workers over time, conditional on life expectancy.[10] Due to feedbacks between the direction of technical change and the skill composition of the workforce, in the long run the economy will converge to a situation where either every worker is skilled $\mu_0^\star = 0$, or unskilled $\mu_1^\star = 1$. Initial conditions play a prominent role in the direction the economy will take at first.

If $\mu_0 < \mu_u^\star$, the relative weight of the skill-intensive sector in aggregate production starts to rise and so does the skill premium, increasing the returns to skills and thereby providing incentives to invest in education. The share of unskilled workers therefore begins to decrease, which in turn reinforces the direction of technical change, biased towards the skilled sector. The skill premium keeps on increasing and the share of unskilled workers converges to $\mu_0^\star = 0$. The unskilled sector eventually disappears, every worker is skilled and employed in the skill-intensive sector and the productivity of the labor input in the production function is high (since $A^s > A^u$).

On the contrary, if If $\mu_0 > \mu_u^\star$, the economy takes another route: the unskilled sector starts to gain weight in aggregate production relative to the skilled sector and the skill-premium decreases. The unskill-biased nature of technical change lowers the incentives of workers to undertake the educational investment required to work in the skilled sector, and the share of unskilled workers starts to increase. Through the same mechanism, this strengthens the relative importance of the unskilled sector, while the skilled sector starts to shrink. There is a progressive loss of skills in the labor force as the number of educated workers declines. This mirrors the episode of deskilling that occurred during the first half of the Industrial Revolution, with the disappearance of skilled artisans and the transition from workshop to factories, the reduction in literacy rates and the general surge in the demand for unskilled labor. Provided nothing happens, the skilled sector ultimately vanishes and the share of unskilled workers converges to $\mu_1^\star = 1$.

As the value of $\mu_u^\star$ depends on ϕ, the life expectancy of workers' is crucial in determining which path the economy will initially engage in: for a given μ_0, a low life expectancy as

[10]Note that if $A \geq e^2$, the proposition is the same for $\phi < \phi_1$ and $\phi \geq \phi_2$. When $\phi \in [\phi_1; \phi_2[$ however, there exists a unique stable steady state $\mu_s^\star$ and two unstable steady states $\mu_{u,a}^\star < \mu_{u,b}^\star$ such that μ_t converges to $\mu_s^\star$ when $\mu_t \in]\mu_{u,a}^\star; \mu_{u,b}^\star[$, to $\mu_0^\star$ when $\mu_t < \mu_{u,a}^\star$ and to $\mu_1^\star$ when $\mu_t > \mu_{u,b}^\star$. The share of unskilled workers may therefore converge to a stable steady state $0 < \mu_s^\star < 1$ for an intermediate level of health. I do not focus on this case as it serves no purpose to the story told in the next sections and will not appear in later simulations as the productivity differential between the two sector will indeed satisfy $A < e^2$.

in Figure 3 makes it more likely that $\mu_0 > \mu_u^\star$ such that technological progress is unskill-biased and the share of unskilled workers increases.

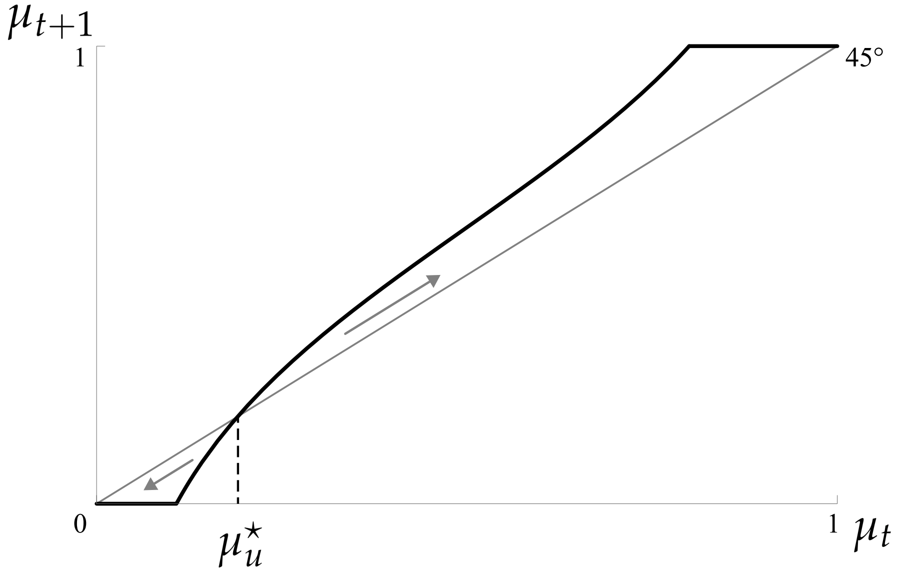

Figure 3. Dynamics for a low life expectancy

More interestingly, once the economy goes down the path of deskilling, improvements in life expectancy may make it change direction. If it is initially low, making the share of unskilled workers increase over time, it is possible that for a given μ_t, a sufficient rise in ϕ increases $\mu_u^\star$ such that $\mu_u^\star > \mu_t$. The effect of an increase in life expectancy is illustrated in Figure 4. In this case, the lengthening of workers' time horizon over which they may reap the fruits of their educational investment is enough to offset the decrease in the skill-premium induced by unskill-biased technical change. The share of unskilled workers in the next period therefore starts to decrease and this in turn influences the direction of technical progress: it turns from being unskill-biased to skill-biased. The positive feedback loop sets in: as the skill-intensive sector gains weight in aggregate production, workers have more and more incentives to undertake education, the share of skilled workers increases and this reinforces the direction of technical change until the economy converges to the steady state where every worker is skilled.

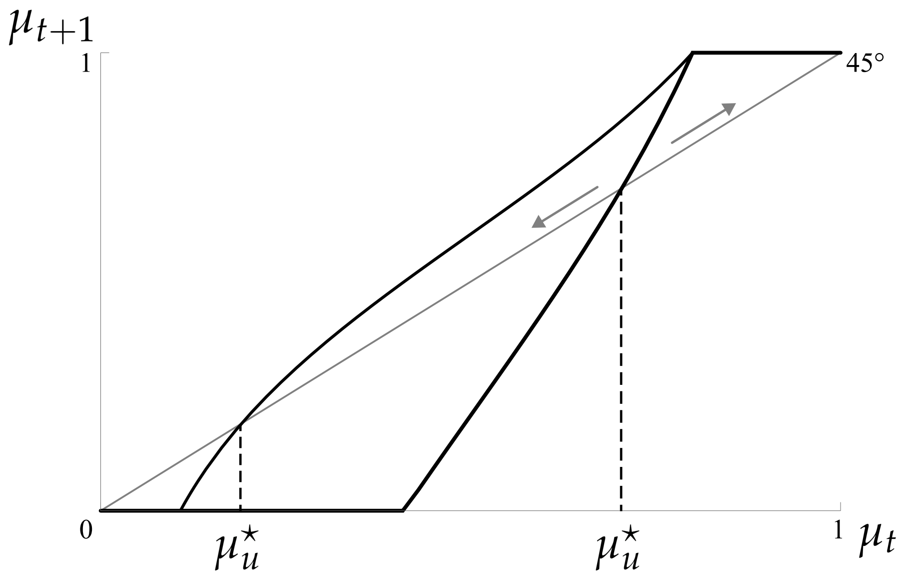

Figure 4. Effect of an increase in life expectancy

5 The provision of public health

Now that we get a sense of how life expectancy affects the dynamics of the economy, I investigate how it is endogenously determined by public health investments. Let us consider that the life expectancy of a worker born in t is a function of public health investments undertaken when she was young m_t, such that $\phi_{t+1} = \phi(m_t) \equiv \frac{\bar{\phi}+m_t}{1+m_t}$. This functional form, often used in OLG models with endogenous longevity such as Raffin & Seegmuller (2014), ensures that ϕ is an increasing and concave function of m_t, and $\phi(0) = \bar{\phi}$, $\phi(\infty) < 1$ and $\infty > \phi'(0) = 1 - \bar{\phi} > 0$. As in Galor & Moav (2006), the government taxes capitalists' wealth at rate τ_t to fund public health investments.[11] This makes capitalists the only ones bearing the cost of workers' improvements in health. Their budget constraints is modified in the following way:

$$c^k_{t+1} + b^k_{t+1} \leq (1-\tau_t)b_t r_{t+1} \equiv I^k_{t+1} \tag{14}$$

And the law of motion of the capital stock is now:

$$K_{t+1} = (1-\tau_t)B_t \tag{15}$$

[11] As discussed above, public health investments in 19th century England were not funded by the taxation of inheritance, but rather by property taxes. However, despite formally being a tax on bequest, τ can also be interpreted as a tax on property, capital or wealth. The latter interpretation is retained here.

Finally, the resource constraint of the government is:

$$m_t = \tau_t B_t \tag{16}$$

England's institutional framework during the Industrial Revolution is often referred to as a 'taxpayer democracy' (see Szreter, 1997 and Aidt, Daunton & Dutta, 2010). Only those duly paying taxes thus had the right to vote. To capture this in the model, I assume that capitalists detain the political power to set taxes on their own wealth. τ_t, hence public health investments, is therefore the result of capitalists' utility maximization. Plugging the first order conditions of their optimization problem back into their utility function yields:

$$\tau_t = \text{argmax}\{\log I^k_{t+1} + C\} \tag{17}$$

Where $C = (1-\beta)\log(1-\beta) + \beta \log \beta < 0$ is a constant. Let us assume that $\log I^k_{t+1} + C > 0$ to ensure positive utility, and note that capitalists choose τ_t to maximize their total wealth – or capital income $I^k_{t+1} = (1-\tau_t)b_t r_{t+1}$. By definition $I^k_t = \alpha Y_t$, and this amounts to maximizing output in $t+1$. However, when taking this decision, capitalists do not observe the future relative productivities of each sector. This is because the level of public health investment they will choose will determine the future skill composition of the labor force, which in turn will give the direction of technological progress. Just as workers, I therefore assume they base their expectation of future technology $x_{t+1} = x(\mu_{t+1})$ on current technology $x_t = x(\mu_t)$ instead, in a myopic fashion. Two things are worth noting. First, the tax rate chosen by capitalists will therefore only maximize expected output rather than actual future output. Second, it will also not maximize welfare as capitalists do not incorporate workers' utility gain from improvements in life expectancy in their decision. Recalling that $B_t = \alpha\beta Y_t$, let us rewrite capitalists' *expected* output Y^k as follows:

$$Y^k_{t+1} = (\alpha\beta(1-\tau_t)Y_t)^\alpha \left\{\phi(\tau_t Y_t) \cdot \left[(A^u\mu_t)^{\frac{1}{1-\alpha}}\Lambda(\phi(\tau_t Y_t),\mu_t) + (A^s(1-\mu_t))^{\frac{1}{1-\alpha}}(1-\Lambda(\phi(\tau_t Y_t),\mu_t))\right]\right\}^{1-\alpha} \tag{18}$$

Capitalists therefore choose τ_t to maximize expected output Y^k_{t+1}, taking μ_t and Y_t as given. A greater tax burden has a negative effect on output by reducing the capital stock, but this may be offset by two positive effects on the labor factor: public health investments directly increase the labor supplied by each worker[12] and indirectly, by raising the returns to education, reallocate workers from the unskilled sector to the more productive

[12] As stated earlier, ϕ_{t+1} can be interpreted as either the number of surviving workers in $t+1$ or as their life expectancy. In any case, an increase in ϕ_{t+1} raises total labor supply: either one considers more people are working, or that each individual works a longer period of time. The latter interpretation is favored here.

skill-intensive sector.

Recall the Kuhn Tucker conditions:

$$\frac{\partial Y_{t+1}^k}{\partial \tau_t} \leq 0 \quad ; \quad \tau_t \geq 0 \quad ; \quad \tau_t \cdot \frac{\partial Y_{t+1}^k}{\partial \tau_t} = 0$$

Considering the cases where $\tau_t = 0$ and $\tau_t > 0$, I obtain:

$$\begin{aligned} Y_t &\leq \frac{\bar{\phi}}{\beta(1-\alpha)(1-\bar{\phi})} \frac{\omega(\mu_t) - [\omega(\mu_t) - 1]\,\Lambda(\bar{\phi}, \mu_t)}{\omega(\mu_t) - [\omega(\mu_t) - 1]\left(\Lambda(\bar{\phi}, \mu_t) + \bar{\phi}\Lambda_\phi(\mu_t)\right)} \quad ; \quad \text{for} \quad \tau_t = 0 \\ \frac{(1-\tau_t)Y_t}{(1+\tau_t\alpha\beta Y_t)} &= \frac{\bar{\phi} + \tau_t\alpha\beta Y_t}{\beta(1-\alpha)(1-\bar{\phi})} \frac{\omega(\mu_t) - [\omega(\mu_t) - 1]\,\Lambda(\phi(\tau_t, Y_t), \mu_t)}{\omega(\mu_t) - [\omega(\mu_t) - 1]\left[\Lambda(\phi(\tau_t, Y_t), \mu_t) + \phi(\tau_t, Y_t)\Lambda_\phi(\mu_t)\right]} \quad ; \quad \text{for} \quad \tau_t > 0 \end{aligned}$$

Where $\omega(\mu_t) = \left(\frac{A^s}{A^u}\frac{1-\mu_t}{\mu_t}\right)^{\frac{1}{1-\alpha}}$ is the current skill-premium on which capitalists base their expectations.

As in Galor & Moav (2006), this defines a threshold level of aggregate bequests below which $\tau_t = 0$ because capitalists perceive the returns to skills are lower than the returns to capital. Rearranging, I express the result in the next proposition:

Proposition 2. *The tax rate in period t, τ_t, is is given by*

$$\tau_t = \tau(\mu_t, Y_t) \begin{cases} = 0 & \text{for} \quad Y_t \leq \tilde{Y}_t \\ > 0 & \text{for} \quad Y_t > \tilde{Y}_t \end{cases}$$

$$\textit{where } \tilde{Y}_t = \frac{\bar{\phi}}{\beta(1-\alpha)(1-\bar{\phi})} \frac{\omega(\mu_t) - [\omega(\mu_t)-1]\Lambda(\bar{\phi},\mu_t)}{\omega(\mu_t) - [\omega(\mu_t)-1]\left(\Lambda(\bar{\phi},\mu_t) + \bar{\phi}\Lambda_\phi(\mu_t)\right)} \equiv \tilde{Y}(\mu_t)$$

The novelty is that the threshold $\tilde{Y}(\mu_t)$ is not constant. Instead, it varies with the direction of technical change of which the skill-premium is an intuitive indicator. To see how changes in relative productivities of the skilled and unskilled sector influence the provision of public health, I investigate how this threshold moves with the current skill premium ω_t according to which capitalists set the tax rate.

Corollary. *Unskill-biased technical change reduces capitalists' incentives to provide public health.*

It is possible to show that $\partial\tilde{Y}_t/\partial\omega_t < 0$ for $\mu_t \in]\underline{\mu}; \overline{\mu}]$: and $\partial\tilde{Y}_t/\partial\omega_t = 0$ otherwise. Therefore, for a given level of output Y_t, skill-biased technological change raises the returns to public health investments for capitalists: it increases the productivity differential between the two sectors and thereby the benefits of reallocating workers from the least productive unskilled sector to the skilled sector. In addition, it also increases the number of workers who choose to make the educational investment for a given improvement in longevity.

On the other hand, when technological change is unskill-biased, the productivity differential between the two sector narrows down, and the lower returns to skills in aggregate production render public health investments less attractive to capitalists. This is why in a period of deskilling, workers' health may stagnate despite economic growth because of a lack of public health measures. If output grows faster than the threshold $\tilde{Y}(\mu_t)$ and eventually exceeds it, capitalists decide to set a positive tax rate on their own wealth to fund public health.

When μ_t is outside the interval $]\underline{\mu};\overline{\mu}]$ however, one of the two sectors has vanished and the only profit capitalists derive from investing in public health is through the direct effect such investments have on workers' productivity.

The timing at which output passes the threshold $\tilde{Y}(\mu_t)$ and the tax rate to fund public health investments turns positive appears crucial for the dynamics of an economy that experiences an episode of deskilling. If the returns to skills exceed those of capital when the share of unskilled workers is not yet too large, improvements in life expectancy may change the course of technological progress and reverse the deskilling trend. The positive feedbacks between increases in the number of skilled workers, technological change that becomes skill-biased and the increasing returns to skills in aggregate production leads to a virtuous circle leading the economy towards a steady state with only skilled workers and a high rate of TFP growth. If the tax rate turns positive when the share of unskilled workers is already too substantial, public health investments may not be enough to stop the deskilling process, but only slow it down. Improvements in life expectancy are too modest to reduce the share of unskilled workers and thereby trigger skill-biased technological change, they only delay the convergence to a steady state with only unskilled workers and no TFP growth. In the next section, I provide a numerical simulation of the dynamics of the model to show how public health investments may have triggered a switch from unskill- to skill-biased technological progress and the transition to a regime of sustained growth in the late 19th century in England.

6 Deskilling during the British Industrial Revolution

The dynamics of the model is fully characterized by the following system of equations:

$$\begin{aligned} Y_{t+1} &= Y(Y_t, \mu_t, \tau_t, z_{t+1}) \\ \mu_{t+1} &= \Lambda(Y_t, \mu_t, \tau_t) \\ \tau_t &= \tau(Y_t, \mu_t) \\ z_{t+1} &= (1 + \eta(1 - \mu_t)) \cdot z_t \end{aligned}$$

Given the nonlinear nature of the system, I simulate the model numerically to show how well it accounts for key features of the British Industrial Revolution. The main objective is to replicate the episode of deskilling experienced during the first half of the Industrial Revolution in England, when technological progress was unskill-biased. The aim is to generate an endogenous transition from unskill- to skill-biased technological progress that is triggered by improvements in life expectancy. For this to happen, the returns to skill must exceed the returns to capital early enough to allow public health investments to stem the vicious feedback between unskill-biased technical change and the increasing share of unskilled workers. The capital-to-labor ratio must therefore increase fairly quickly relative to the trajectory of the share of unskilled workers: when the latter surges, the increase in life expectancy needed to reverse the trend becomes grows as well and the required public health investments become too costly.

There is a range of parameters values that could yield the desired qualitative results. Capitalists propensity to save β is an important driver of physical capital accumulation. A high saving rate ensures indeed a reasonable growth of the capital-to-labor ratio and, with diminishing returns to capital, makes workers' skills more profitable earlier during development. In this baseline calibration, I set $\beta = 0.32$. To force the trajectory of the share of unskilled workers not to be too steep, the ratio of sector-specific productivities A^s/A^u need to be high enough. I set $A^s = 4$ and $A^u = 1$. One caveat is that given the functional forms chosen on the production side, the skill-premium will take values that will not match existing data.[13] In the baseline calibration, the skill premium starts slightly above 50 which is much greater than what has been ever observed. This paper does not ambition to be quantitatively precise, but rather explain qualitatively patterns that the English economy experienced during its industrialization, and the calibration is done in this spirit.

[13] Evidence for the evolution of the skill-premium during the Industrial Revolution are scarce and obviously imperfect, see Clark (2005) and Van Zanden (2009) for notorious examples.

The other parameters are chosen for various reasons. $\bar{\Delta}$ is the most arbitrary and strongly influences the trajectory of the share of unskilled workers. I set $\bar{\Delta} = 1.55$ to make sure it does not either surge or plunge too fast. The capital intensity of the production function is set at $\alpha = 0.3$, which is rather standard. The parameter governing the growth rate of TFP $\eta = 0.7$ is set such that an economy that has converged to a balanced growth path with only skilled workers grows at a rate around 2.7%. I normalize z_0 to one. I set $\mu_0 = 0.2$ to match observations by de Pleijt and Weisdorf (2017) of a share of unskilled workers around 20% in at the start of the 18th century. To ensure $\mu_0 > \mu_u^\star$, I choose the lower bound for life expectancy to be $\bar{\phi} = 0.3$. Finally, $Y_0 = 0.5$ such that $Y_0 < \tilde{Y}_0 \approx 1$ and there are no public health investments at the beginning. Finally, I consider each period corresponds to roughly 25 years and solve the model for ten periods to cover a time span of 250 years, starting from the first quarter of the 18th century, when the deskilling episode began. The resulting dynamics of the economy is given in the following figures.

Figures 5 and 6 show the key feature of the model: the interplay between the skill composition of the labor force and the direction of technical change. Initial conditions are such that the share of unskilled workers starts to slowly but steadily increase at the beginning of the 18th century. Recall that in order to capture innovations being driven by a Schumpeterian market-size effect, it is assumed that the relative weight of each sector in aggregate production depends on the number of workers employed there. A rise in the number of unskilled workers therefore increases the relative productivity of the unskilled sector relative to the skilled sector, and the skill-premium starts to decline: technological progress is *unskill-biased*. As the returns to skill lessen, workers' incentives to invest in education follow and the share of unskilled workers further increases, fueling the unskill-biased march of technological progress.

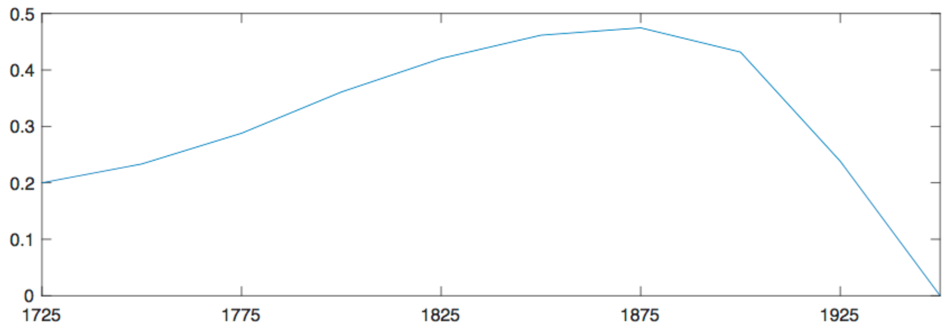

Figure 5. The share of unskilled workers

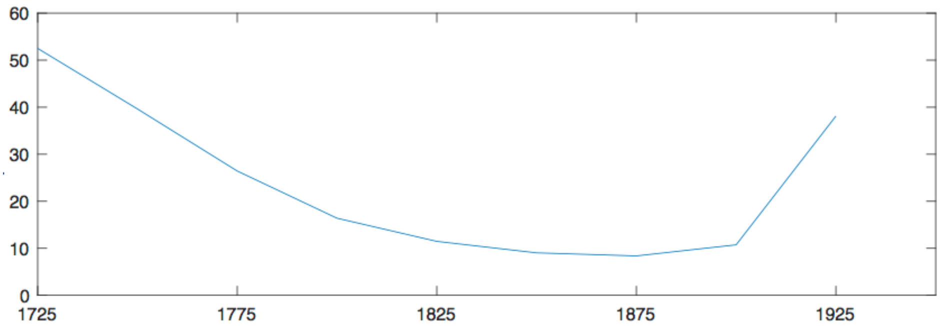

Figure 6. Skill-premium

As both the share of unskilled workers and the importance of the unskill-intensive sector rise, output starts to grow from physical capital accumulation, rising productivity of unskilled labor and TFP growth. The direction of technological progress reduces the returns to skill in production, and hence capitalists' incentives to finance public health investments. However, the capital-to-labor ratio gradually increases and because of diminishing returns, at some point the returns to skills surpass those of physical capital and capitalists decide to set a positive tax rate on their own wealth (Figure 7).

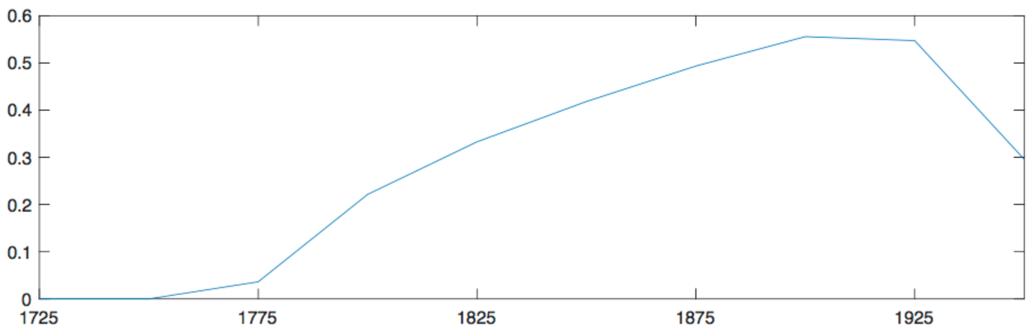

Figure 7. Tax rate on bequests

A caveat of the model is that capitalists decide to invest in health-related infrastructure as early as 1800 (Figure 8), date at which the tax rate on wealth is slightly above 20%. This is much earlier than the last quarter of the 19th century, when public health investments really occurred in England. However, as shown in Figure 8 and 9, public health expenditure remain quite low and life expectancy increases very slowly. Improvements in the health of workers are thus very modest for most of the 19th century, despite output growth. By slightly increasing the returns to education however, such improvements partially offset the negative effect of unskill-biased technological progress on workers' incentives. It is not enough yet to reverse the trend of deskilling, but it slows down the rise of the share of unskilled workers and thereby curb the direction of technological progress.

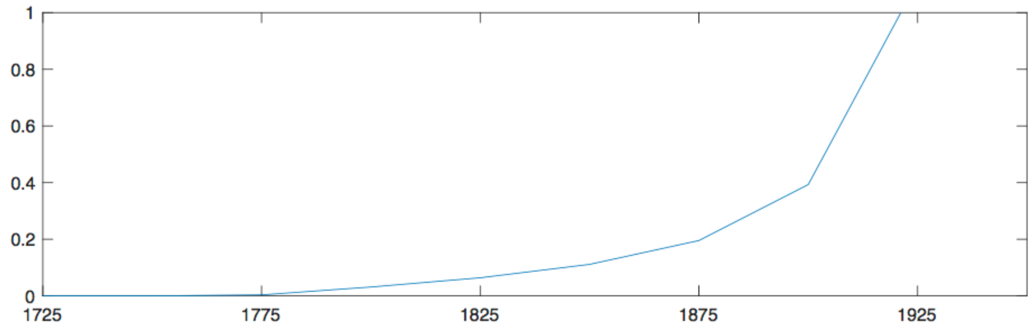

Figure 8. Public health investments

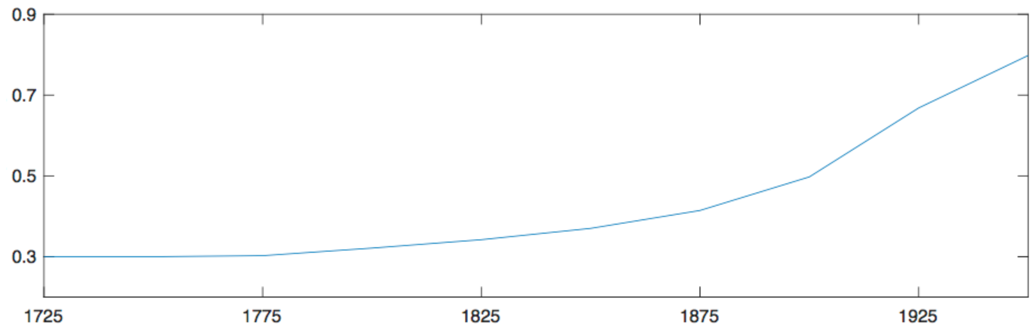

Figure 9. Workers' life expectancy

As output keeps growing, taxes increase substantially, reaching a peak in the last quarter of the 19th century, and public health investments surge. At this stage of development, improvements in workers' life expectancy and the ensuing incentives to invest in education are such that the share of unskilled workers starts to decrease after a long episode of deskilling. The turn of the 20th century is therefore a tipping point. The increased number of skilled workers finally direct innovation towards the skilled-labor-using sector, and technological progress switch from being unskill- to skill-biased. This is can be interpreted as the emergence of the capital-skill complementarity documented by Goldin & Katz (1998). As skills gain prominence in aggregate production, the skill premium rises and workers' incentives to acquire education increase. The positive feedback loop between the direction of technological progress and the skill composition of the labor force sets in. Ultimately, the unskilled-labor using sector vanishes and the economy evolves along a balanced growth path with skilled workers only and a high growth rate of TFP (Figure 10).

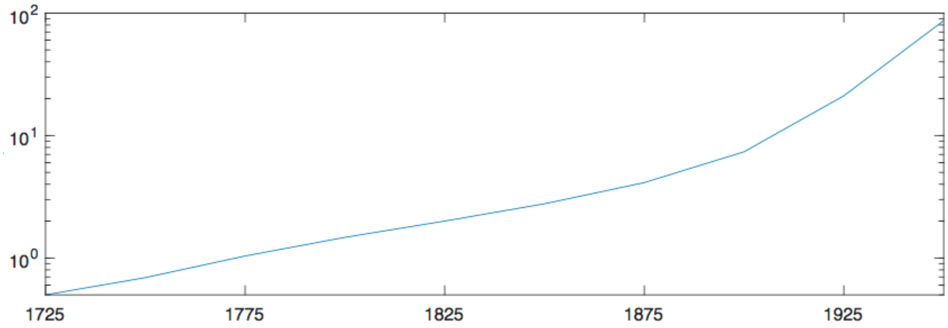

Figure 10. Output

As there are no longer benefits from reallocating workers across sectors once the unskilled sector has disappeared, the tax rate progressively declines. Public health expenditure nevertheless grow with output and life expectancy eventually converge to one.

7 Conclusion

In this paper I propose a theory that can account for the episode of deskilling in England during the Industrial Revolution, as well as an endogenous transition from unskill- to skill-biased technological progress following improvements in life expectancy in the late 19th century.

Feedback loops between the average level of skills in the labor force and the direction of technological progress initially set up a vicious circle where workers have less and less incentives to invest in education. The unskill-biased nature of technological progress reduces the role of skills in aggregate production, which lowers the incentives of profit-maximizing capitalists to tax their own wealth to finance improvements in workers' health. As in Galor & Moav (2006), only when the returns to human capital exceeds those of physical capital will capitalists consent to wealth taxation. However, the timing of public health investments is crucial to reverse the deskilling process and make technological progress switch from being unskill- to skill-biased. Contrary to models of long-run growth, a take-off to a regime of sustained economic growth is not inevitable. Instead, the share of unskilled workers may converge to one and the economy get stuck in a poverty trap with no increase in TFP and a poor life expectancy.

The theory also relaxes the tight link between life expectancy and output growth. Health instead is determined through political decisions and may stagnate despite economic development, provided the costs of its provision outweigh the benefits for the ruling class. In this paper I assume that public health investments are undertaken if and only if they maximize the welfare of the capitalist class, but many other factors played a role in the decision to engage in such big public works. Economic historians such as Simon Szreter have notably emphasized the enfranchisement of the working class that pushed towards its own interests, while acute politicians seized on the electoral opportunity. Both explanations are not mutually excludable as it is likely that an interplay between the bargaining power of the working class coupled with capitalists' own interest led to the provision of public goods such as health infrastructure and education.

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Appendix

Proof of proposition 1

(i) To look for potential steady states conditional on the value of ϕ, let us set $\mu_{t+1} = \mu_t = \mu^\star$ and look at $\mu^\star = \Lambda(\mu^\star, \phi)$. Two trivial steady states are $\mu^\star = 0$ and $\mu^\star = 1$. To find the others, let us consider the function $F(\mu^\star, \phi) \equiv \Lambda(\mu^\star, \phi)/\mu^\star$ and find the solutions to the equation $F(\mu^\star, \phi) = 1$ in the interval $]\underline{\mu}; \overline{\mu}]$:

$$\frac{1}{\mu^\star}\left[1 - \frac{\phi}{(1-\alpha)\bar{\Delta}} \log\left\{A \cdot \frac{1-\mu^\star}{\mu^\star}\right\}\right] = 1$$

First, note that F is continuous, $F(\underline{\mu}, \phi) = 0$ and $F(\overline{\mu}, \phi) = 1 + 1/A > 1$. There is therefore at least one possible solution. Furthermore, $F_\phi < 0$. Now, let us study the sign of the derivative of F with respect to $\mu^\star$:

$$F_{\mu^\star} = \frac{1}{\mu^{\star 2}}\left\{\frac{\phi}{(1-\alpha)\bar{\Delta}}\left[\log\left\{A \cdot \frac{1-\mu^\star}{\mu^\star}\right\} + \frac{1}{1-\mu^\star}\right] - 1\right\}$$

It follows that $F_{\mu^\star} = 0$ when $\log\left\{A \cdot \frac{1-\mu^\star}{\mu^\star}\right\} + \frac{1}{1-\mu^\star} = (1-\alpha)\bar{\Delta}/\phi$. For clarity, denote the left-hand side by $H(\mu^\star)$ and the right-hand side by $\kappa(\phi)$ and look for the solutions of $H(\mu^\star) = \kappa(\phi)$. By definition, $\underline{\mu}$ is such that $\log\left\{A \cdot \frac{1-\mu^\star}{\mu^\star}\right\} > (1-\alpha)\bar{\Delta}/\phi$, hence $H(\underline{\mu}) > \kappa(\phi)$, and $H(\overline{\mu}) = 1 + A$. $H'(\mu^\star) = (2\mu^\star - 1)/[\mu^\star(1-\mu^\star)^2]$, therefore $H'(\mu^\star) < 0$ when $\mu^\star < 1/2$, $H'(\mu^\star) = 0$ when $\mu^\star = 1/2$, and $H'(\mu^\star) > 0$ when $\mu^\star > 1/2$. There are several cases to consider, depending on the value of $\kappa(\phi)$, with $\kappa'(\phi) < 0$.

When $\phi < \phi_1 \equiv (1-\alpha)\bar{\Delta}/(1+A)$, $H(\overline{\mu}) < \kappa(\phi)$ and the equation $H(\mu^\star) = \kappa(\phi)$ has a unique solution $\mu_a < 1/2$. $F(\mu^\star, \phi)$ is therefore increasing in the interval $]\underline{\mu}; \mu_a[$ and decreasing in $]\mu_a; \overline{\mu}]$. This implies that the equation $F(\mu^\star, \phi) = 1$ has a unique solution $\mu^\star < 1/2$.

When $\phi \geq \phi_2 \equiv (1-\alpha)\bar{\Delta}/(2+\log A)$, $H(\mu^\star) \geq \kappa(\phi)$ since $H(1/2) \geq \kappa(\phi)$, and $F_{\mu^\star} \geq 0$. The equation $F(\mu^\star, \phi) = 1$ therefore has a unique solution.

When $\phi_1 \leq \phi < \phi_2$, the equation $H(\mu^\star) = \kappa(\phi)$ has two solutions, μ_1 and μ_2, with $\mu_1 < 1/2 < \mu_2$. $F_{\mu^\star}$ is positive for $\mu^\star < \mu_1$, negative for $\mu_1 < \mu^\star < \mu_2$, and positive again for $\mu^\star > \mu_2$. The equation $F(\mu^\star, \phi) = 1$ may therefore have a unique solution if $F(\mu_1, \phi) > F(\mu_2, \phi) > 1$ or $1 > F(\mu_1, \phi) > F(\mu_2, \phi)$, or three solutions if and only if $F(\mu_1, \phi) > 1 > F(\mu_2, \phi)$. A necessary and sufficient condition for having three steady states is $A > e^2$.
Proof: suppose $F(1/2, \phi_2) < 1$, which is the case when $A > e^2$. Since the function F is continuous and decreasing in ϕ for all $\mu^\star$, there exists a $\epsilon > 0$ such that for $\phi = \phi_2 - \epsilon$, $F(\mu_1, \phi_2 - \epsilon) > 1 > F(1/2) > F(\mu_2, \phi_2 - \epsilon)$. $A > e^2$ is therefore sufficient to ensure three solutions. To show it is also necessary, suppose $F(1/2, \phi_2) = 1$. In this case, $F_{\mu^\star} > 0$ for $\mu^\star > 1/2$ and therefore $F(\mu^\star, \phi_2) > 1$ for $\mu^\star > 1/2$. Now consider another ϵ such that for $\phi = \phi_2 - \epsilon$, $F(\mu_1, \phi_2 - \epsilon) > F(1/2, \phi_2) > F(\mu_2, \phi_2 - \epsilon)$. Since $\mu_2 > 1/2$ and F is decreasing with ϕ for all $\mu^\star$, it follows that $F(\mu_2, \phi_2 - \epsilon) > F(\mu^\star, \phi_2) > 1$. There is a unique steady state: the condition $A > e^2$ is therefore necessary. QED.

(ii) For simplicity, let us make the assumption that $A < e^2$, so that there are three solutions to the equation $\Lambda(\mu^\star) = \mu^\star$. There are two stable steady states $\mu_0^\star = 0$ and $\mu_1^\star = 1$ and one unstable steady state $\mu_u^\star$ in $]\underline{\mu}; \overline{\mu}]$. The stability of both $\mu_0^\star = 0$ and $\mu_1^\star = 1$ follows from $\Lambda'(\mu_0^\star) = \Lambda'(\mu_1^\star) = 0$. $\mu_u^\star$ is unstable because $\Lambda'(\mu_u^\star) > 1$.
Proof: $\Lambda'(\mu_u^\star) > 1 \Leftrightarrow \phi/[(1-\alpha)\bar{\Delta}] > (1-\mu_u^\star)\mu_u^\star$. Now, rearranging $\Lambda(\mu_u^\star) = \mu_u^\star$ yields $(1-\mu_u^\star)\mu_u^\star = \phi/[(1-\alpha)\bar{\Delta}] \log\{A(1-\mu_u^\star)/\mu_u^\star\}$. Plugging this into $\Lambda'(\mu_u^\star) > 1$, we see that it amounts to $1/\mu_u^\star - \log\{(1-\mu_u^\star)/\mu_u^\star\} > \log A$. Let us denote the left hand side by $h(\mu_u^\star)$. A sufficient condition is therefore $h(\mu_u^\star) \geq 2$ since $\log A < 2$ by assumption. $h'(\mu_u^\star) < 0$ for $\mu_u^\star < 1/2$, $h'(\mu_u^\star) = 0$ for $\mu_u^\star = 1/2$, and $h'(\mu_u^\star) > 0$ for $\mu_u^\star > 1/2$. $h''(1/2) > 0$ so $h(1/2)$ is a global minimum and $h(1/2) = 2 \geq 2$, therefore $h(\mu_u^\star) \geq 2$, which concludes the proof. QED.

(iii) To investigate the effect of workers' life expectancy on the dynamics of the skill composition of the labor force, let us look at how $\mu_u^\star$ varies with ϕ. To do so, consider $\mu_u^\star - \Lambda(\mu_u^\star) = 0$ and use the implicit function theorem to get $\partial\mu_u^\star/\partial\phi = \frac{\partial\Lambda/\partial\phi}{1-\Lambda'(\mu_u^\star)}$. Since $\Lambda/\partial\phi < 0$ and $\Lambda'(\mu_u^\star) > 1$, it follows that $\partial\mu_u^\star/\partial\phi > 0$. QED.