

# Access to health care, medical progress and the emergence of the longevity gap: a general equilibrium analysis\*

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## Abstract

We study skill- and income-related differences in the access to health care as drivers of longevity inequality from a theoretical life-cycle as well as from a macroeconomic perspective. To do so, we develop an overlapping generations model populated by heterogeneous agents subject to endogenous mortality. We model two groups of individuals for whom differences in skills translate into differences in income and in the ability to use medical technology effectively in curbing mortality. We derive the skill- and age-specific individual demand for health care based on the value of life, the level of medical technology and the market prices. Calibrating the model to the development of the US economy and the longevity gap between the skilled and unskilled, we study the impact of rising effectiveness of medical care in improving individual health and examine how disparities in health care utilisation and mortality emerge as a consequence. In so doing, we explore the role of skill-biased earnings growth, skill-bias in the ability to access state-of-the art health care and to use it effectively, and skill-related differences in health insurance coverage. We pay attention to the macroeconomic feedback, especially to medical price inflation. Our findings indicate that skill-bias related to the effectiveness of health care explains a large part of the

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increase in the longevity with earnings-related differences in the utilisation of health care taking second place. Both channels tend to be reinforced by medical progress.

**Keywords:** health care spending, inequality, life-cycle model, life-expectancy gap, medical price inflation, medical progress, overlapping generations, skill-biased earnings growth.

**JEL-Classification:** D15, I11, I12, I24, J11, O33, O41.

## 1 Introduction

Growing disparity in longevity across socioeconomic groups has been extensively documented for the US over the past couple of decades (Hummer and Hernandez 2013; Chetty et al. 2016; Case and Deaton 2017).<sup>1</sup> Such a development is unwelcome for a number of reasons. First, it may conflict with principles of social justice (Fleurbaey and Schokkaert 2012) and reflect a general increase in economic inequality (Autor et al. 2008; Saez and Zucman 2013) that is detrimental to social cohesion. Second, inequalities in health have been shown to cause a drag on economic growth (Grimm 2011). Third, the variation in life span due to premature death slows down the overall increase in life expectancy at the population level (Vaupel et al. 2011) and, thus, societal progress against an important measure of human development. Finally, inequality in longevity has considerable implications for the fairness of pension schemes and the incentives they generate across different social strata (National Academy of Sciences 2015; Lee and Sanchez-Romero 2017; Sanchez-Romero and Prskawetz 2017).

Three key sources of health-related inequalities can be identified: Differences in behaviours (e.g. Cutler and Lleras-Muney 2010; Cutler et al. 2011), differences in the socio-economic environment (e.g. Chetty et al. 2016), and differences in the access to innovative health care (e.g. Phelan and Link 2005; Glied and Lleras-Muney 2008).<sup>2</sup> This

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<sup>1</sup>See OECD (2017) for evidence on similar trends across other industrialised countries.

<sup>2</sup>For general surveys and summaries of the debate on what are the drivers of health-related inequality see Deaton (2003), Phelan et al. (2010), Woolfe and Braveman (2011), Truesdale and Jencks (2016) and Case and Deaton (2017).

last source is of particular interest for three reasons: First, by being directly linked to the design of the health care system, this channel opens a straightforward way for the policy maker to address health-related inequalities by way of implementing appropriate policies. Conversely, the design of the health care system itself may result in unequal access and health outcomes. Second, differential access to health care is governed by two key channels: (i) income differences and differences in health insurance coverage will translate into *differences in the utilisation* of health care of *given effectiveness*; and (ii) differences in the ability to access or to use appropriately the most advanced medical treatments translate into *different effectiveness* of health care for a *given level of utilisation*. Third, the income dynamics on the demand side and medical progress on the supply side may, therefore, be particularly good candidates for explaining the ongoing widening of the longevity gap.<sup>3</sup>

While there is a considerable body of empirical literature on the access to health care (reviewed in Section 2 below), this is mostly based on particular case studies with a focus on either income differences or on differences in the utilisation of innovative health care. Against this backdrop, this paper seeks to provide answers to the following set of questions: (i) How does the inequality in longevity emerge from the interplay of differential earnings and earnings growth, differential access to the most effective medical treatments, and differential health insurance coverage; (ii) what quantitative importance can be assigned to these channels; and (iii) how are these channels shaped by medical progress and by general equilibrium dynamics, in particular the development of the price for health care?

In order to address these questions, we develop an overlapping generations model populated by heterogeneous agents subject to endogenous mortality. We model two groups of individuals who differ in the level of their skills (or educational attainment) and, according to their labour productivity, receive differential earnings. In addition, we assume the ability to access and use new medical technology effectively to increase with skills, implying a

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<sup>3</sup>By medical progress we refer to the development and adoption of both new medical technology and innovative medical practice both of which raise the effectiveness of medical treatments.

differential impact of health care on survival. Individuals maximise their life-cycle utility by purchasing a consumption good from which they derive utility and elective health care with a view to affecting their survival prospects, the latter proxying also for an individual's health status. Assuming that the health status determines non-elective (emergency) health care, we keep track of this additional and quantitatively important determinant of health care spending. The economy consists of two sectors: a medical sector providing (elective and non-elective) health care, and a production sector producing consumption and capital goods. The relative price of health care is determined endogenously and depends on the sector-specific use of production factors and their general equilibrium prices.

We derive the age-specific individual demand for health care based on the value of life, the level of medical technology and the consumer price of health care. Given the income level as well as the effectiveness of medical care within each of the two groups, we are able to determine a baseline level of mortality inequality. We then employ counterfactual analysis to identify the impact on health care utilisation and longevity of (i) skill-biased technological progress in the production sector, leading to a widening in the earnings gaps; (ii) skill-bias in the access to state-of-the art medical care and its effective application (or shorter: skill-bias in medical effectiveness); and (iii) skill-biased coverage of health insurance. We pay particularly close attention to macroeconomic effects caused by differential productivity growth and medical progress on the price for medical care and its feedback on the individual demand for health care within the two groups. When studying the role of productivity growth, we follow Baumol's (1967) theory, according to which productivity gains in capital-intensive sectors do not only cause income growth but also led to rising production costs in labour-intensive sectors, such as health care. Given that income growth disproportionately benefits high skilled individuals, whereas the price for health care rises for all individuals, this may also imply a widening gap in the access to health care. We explore the relevance of this channel in affecting mortality inequality.

We calibrate the model to reflect the development of US income and life expectancy over the time span 1960-2015. In so doing we follow Cutler et al. (2006) and Ford et al. (2006) in attributing 50% of the reduction in mortality to changes in the utilisation and effectiveness of health care. Focusing in our analysis on the role of health care, we assume a constant exogenous trend for the remaining 50% that is in line with the data. Here, we make use of recent evidence by Cutler et al. (2011) showing for the US that the education gap in mortality that can be attributed to behavioural channels has remained remarkably stable over the time frame 1971-2000.

We replicate in our model the increase by some 2.1 years in the life expectancy gap between the 50 percent top earners (representing the skilled) and the 50 percent bottom earners (representing the unskilled) in the US over the time span 1960-2015. We find that about 19 percent of the increase are explained by skill-biased earnings growth, about 57 percent by skill-bias in medical effectiveness, and 5 percent by health insurance, whereas 24 percent of the increase are explained by the fact that the initial (1960) gap in earnings translates into a difference in health care spending which owing to medical progress leads to a widening gap in survival. Thus, the skilled are able to expand their relative survival opportunities predominantly (i) due to a rising ability and propensity to spend on health care in the presence of skilled-biased earnings growth; (ii) due to their better access to state-of-the-art care for any given level of health care spending, an effect which is exacerbated due to medical progress overall;<sup>4</sup> and (iii) due to a complementarity between income and medical progress such that their higher consumption of health care from the outset allows them to participate to an increasing extent in the benefits from medical advances. Finally, we find that while medical prices increase by a factor of about 1.5 over the time span 1960-2015, this does not contribute to a widening in the longevity gap.

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<sup>4</sup>Intuitively, access to the state-of-the-art treatment for a given condition only matters once effective treatments have been developed. Thus, skill-related differences in access are reinforced over time with the advent of more and more effective treatments.

The remainder of the paper is set out as follows. Section 2 provides a review of some recent empirical and theoretical literature on health inequality within life-cycle models with a particular focus on the utilisation of health care. Section 3 introduces the model; Section 4 presents the equilibrium allocation; Section 5 introduces the calibration of the model (Section 5.1) and provides the results of our numerical analysis (Sections 5.2 and 5.3); Section 6 discusses policy implications and the role of medical progress; Section 7 concludes. Some mathematical derivations and details on the numerical simulation have been relegated to an Appendix.

## 2 Literature

In this section, we briefly review the empirical and theoretical literature that is pertinent to our analysis. As we have argued in the introduction, the literature suggests two particularly prominent drivers of unequal access to health care: First, skill-biased technological progress across many sectors of the economy has been extensively documented to generate a widening income gap in advantage of the skilled and educated [see Acemoglu and Autor (2011) for an overview]. A large empirical literature shows how income differences translate into differences in the consumption of health care and, more specifically, in the access to highly effective state-of-the-art health care (e.g. Getzen 2000; Bago d’Uva and Jones 2009; Vallejo-Torres and Morris 2013). Owing to their higher propensity to consume health care, wealthier individuals then tend to participate more strongly in the benefits from medical progress (Goldman and Lakdawalla, 2005). Second, even at the same level of consumption of health care, medical progress is prone to lead to divergent medical outcomes and trends to life expectancy if individuals from higher socioeconomic groups are able to utilise medical advances more effectively (Phelan and Link 2005; Glied and Lleras-Muney 2008; Avitabile et al. 2011; Lange 2011; Hernandez et al. 2018) or have access to higher quality

treatments (Fiva et al. 2014).<sup>5</sup>

Our work ties in with a number of recent papers addressing the income and education related inequality in health outcomes within calibrated life-cycle models. Capatina (2015) studies the role of different health risks over the life-cycle across different strata of education. She does not, however, endogenise the consumption of health care. Ales et al. (2014) study the (social) efficiency of differences in health care spending and, depending on this, in longevity across individuals with different earnings potential. Ozkan (2014) studies the incentives for individuals from different income groups to invest in preventive and curative care in a model in which health shocks lead to a deterioration of a stock of health and higher mortality. He finds that the subsidisation especially of preventive health care for the poor may yield significant welfare gains. Prados (2017) studies the interrelationship between income and health inequality over the working life with a particular focus on the feedback from health on earnings. Finally, Cole et al. (2018) study the impact of recent US reforms aimed at curbing health-related discrimination within the labour and insurance markets on preventive behaviour and welfare when individuals differ in their health.

None of these works addresses the dynamics of the education/income gradient in mortality as a consequence of skill-biased productivity growth and skill-biased access to medical progress. Such an analysis is important, as it provides a sound theoretical basis for understanding and assessing the transmission channels that underlie the empirical findings on the impact of education and income on individuals' propensity to benefit from health care and medical progress. To our knowledge, the only other theoretical approach towards understanding the role of differential access to medical progress is Goldman and Lakdawalla (2005). Studying a static model in which an individual maximises utility depending on health and consumption, they identify the greater demand for health care on the part of individuals with high socio-economic status (conditional on medical need) as a key condi-

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<sup>5</sup>See Schröder et al. (2016) for a recent systematic review of the literature on the SES gradient in the access to treatment for coronary heart disease, highlighting effects of both income and education.

tion for a differential impact on longevity of productivity growth in the health care sector. This is because an increase in medical productivity, in their case modelled as a decline in the price of health care, tends to boost the demand for health care by more for those with greater socio economic status. While the greater propensity to benefit from medical progress for those with high demand also plays a role in our model, the mechanism goes through the effectiveness of medical technology rather than the productivity of the health care sector. Indeed, in line with the empirical evidence the price in health care is increasing in our model rather than declining. More generally, our paper relates to an emerging literature on the role of medical progress within the macroeconomy (Suen 2009, Chandra and Skinner 2012, Fonseca et al. 2013, Jones 2016, Koijen et al. 2016, Frankovic et al. 2017, Schneider and Winkler 2017, Böhm et al. 2018, Frankovic and Kuhn 2018). Covering various aspects of medical progress, these works do not address its role as a driver of the emerging longevity gap.

### 3 Model

We consider two groups of individuals who differ in their skill (education) level  $i = s, u$ , with  $s$  denoting the skilled and  $u$  denoting the unskilled, respectively. The differences in skills translate into (i) differential labour productivity and, thus, into differential earnings (as documented e.g. in Acemoglu and Autor 2011); and (ii) into differential ability to use medical technology/know-how effectively in order to improve health and survival chances (as documented e.g. in Glied and Lleras-Muney 2008, Avitabile et al. 2011, Lange 2011, Hernandez et al. 2018). Both groups are represented by overlapping generations of individuals who choose consumption and health care over their life-course. We should stress at this point that we are not interested in explaining the causality of income as opposed to education as drivers of inequality in health, nor any reverse causality, but rather in



exploring the channels through which differences in education/skills translate into different participation in the benefits from health care and medical progress. In light of this, we also abstract from the intergenerational transmission of skills and wealth and assume individuals are randomly assigned to either of the skill groups at birth.

### 3.1 Individual Life-cycle

We begin by specifying the mortality process that is underlying our model. We assume the force of mortality,  $\mu = \eta m(h, M)$ , to follow a proportional hazard form, where  $\eta > 0$  is an exogenous shifter of mortality and where

$$m(h, M) = h^{-M}, \tag{1}$$

describes the impact of  $h$  units of elective health care on mortality, with  $M > 0$  measuring its effectiveness. Allowing for heterogeneity across skill types,  $i = s, u$ , age,  $a$ , and time,  $t$ , in regard to the consumption of elective health care,  $h_i(a, t)$ , the exogenous component of mortality,  $\eta_i(a, t)$ , and medical effectiveness,  $M_i(t)$ , we can write the  $(a, t, i)$ -specific force of mortality as<sup>6</sup>

$$\mu_i(a, t) := \eta_i(a, t)m(h_i(a, t), M_i(t)). \tag{2}$$

While  $\eta_i(a, t)$  captures exogenous age- and time-related trends to mortality as well as heterogeneity across skill groups unrelated to the consumption of health care,  $M_i(t)$  can be interpreted as the degree to which an individual of skill type  $i$  has access to innovative treatments at time  $t$  or, equivalently, the degree to which a type  $i$  uses a given set of treatments effectively. Intuitively, we would expect  $0 < M_u(t) \leq M_s(t)$ , implying that unskilled individuals may suffer from restrictions in the access to the most effective health

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<sup>6</sup>We could assume that medical effectiveness also depends on age. We omit age as an argument as we are subsequently not using it in our calibration.

care. Such restrictions may arise from knowledge gaps, from lack of social capital in the communication with physicians, or from less effective use of innovative medicine, e.g. due to lack of compliance with certain treatment paths or due to the negligence in the attention of regular screening. In summary, the extent to which the unskilled suffer from a higher mortality,  $\mu_u(a, t) > \mu_s(a, t)$ , depends (i) on the extent of an exogenous disadvantage  $\eta_u(a, t) > \eta_s(a, t)$  related to life-style and/or living environment, (ii) on the extent to which they consume a lower quantity of elective health care,  $h_u(a, t) < h_s(a, t)$ , and (iii) on their relative disadvantage in the access to (or use of) the most effective form of medical medical care,  $M_u(t) < M_s(t)$ .

We can now formulate the survival function

$$S_i(a, t) = \exp \left[ - \int_0^a \mu_i(\hat{a}, \hat{t}) d\hat{a} \right]$$

as the probability of a type  $i = s, u$  to survive from birth at time  $t_0 = t - a$  through age  $a$  at time  $t$ .<sup>7</sup> Following Chandra and Skinner (2012), Kuhn et al. (2015) and Frankovic et al. (2017) we can interpret survival,  $S_i(a, t)$ , as a proxy of the stock of health at  $(a, t, i)$ . For the representative individual, the assumption that health care can slow down but not reverse the decline of health over the life-course is plausible and well in line with evidence on the gradual accumulation of health deficits (Rockwood and Mitnitski, 2007; Dalgaard and Strulik 2014).

Building on this notion, we assume that besides deciding on the quantity of elective health care,  $h_i(a, t)$ , individuals also receive emergency health care according to a function

$$e(S) = \xi_1 S^{-\xi_2}, \tag{3}$$

with  $\xi_1 \geq 0$  and  $\xi_2 \in [0, 1]$ , depending on their health/survival state,  $S \in [0, 1]$ .

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<sup>7</sup>Note, that  $\hat{t} = t_o + \hat{a}$ .

This reflects the notion that in situations of critical illness, as proxied by a low probability of survival, individuals must consume a quantity of health care  $e > 0$  in order to survive without having a degree of choice. Note that the dependency of emergency care on survival also implies that the consumption of health care tends to be higher close to the time of an individual's death (e.g. Zweifel et al. 1999). When choosing elective health care, individuals internalize the savings on expenditure for emergency health care, as they accrue from higher levels of survival/health over the life-cycle.

Finally, we assume that during each period of their lives individuals enjoy an instantaneous utility

$$u(c) = \frac{c^{1-\sigma}}{1-\sigma} + b, \quad (4)$$

from consumption  $c \geq 0$ , where  $\sigma > 1$  denotes the inverse of the intertemporal elasticity of substitution, and where  $b > 0$  is a constant "pleasure of living" high enough to ensure that  $u(c) > 0$  for all relevant values of consumption.<sup>8</sup>

Based on these ingredients, we can formulate the individual life-cycle problem according to which a representative from group  $i = s, u$  who is born at  $t_0 = t - a$  maximises the present value of the utility stream over their (remaining) life-cycle by choosing a stream of consumption,  $c_i(a, t)$ , and elective health care,  $h_i(a, t)$ , subject to the mortality process and a budget constraint. Formally, the objective is then given by

$$\max_{c_i(a,t), h_i(a,t)} \int_0^\omega e^{-\rho a} u(c_i(a, t)) S_i(a, t) da, \quad (5)$$

where  $\rho$  and  $\omega$  denote the rate of time preference and the maximal attainable age, respec-

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<sup>8</sup>Our assumption  $\sigma > 1$  reflects our calibration in Section 5.1 and is in line with the evidence in Chetty (2006).

tively. The individual faces the following skill-specific state constraints:

$$\dot{S}_i(a, t) = -\mu_i(a, t)S_i(a, t), \quad (6)$$

$$\begin{aligned} \dot{k}_i(a, t) = & r(t)k_i(a, t) + l(a)w_i(t) - c_i(a, t) - \phi_i(a, t)p(t)[h_i(a, t) + e(S_i(a, t))] \\ & -\tau_i(a, t) + \pi_i(a, t) + s(t), \end{aligned} \quad (7)$$

with  $S_i(0, t_0) = 1$ ,  $S_i(\omega, t_0 + \omega) = 0$  and  $k_i(0, t) = k_i(\omega, t) = 0$  as boundary constraints. Survival is reduced over the life-course according to the force of mortality. The individual's stock of assets,  $k_i(a, t)$ , (i) increases with the return on the current stock, where  $r(t)$  denotes the interest rate at time  $t$ ; (ii) increases with earnings,  $l(a)w_i(t)$ , where  $l(a)$ , as specified in (21) below, denotes the exogenous labour supply of an individual at age  $a$  and where  $w_i(t)$  denotes the skill-specific wage rate at time  $t$ ; <sup>9</sup> (iii) decreases with consumption, the price of consumption goods being normalised to one; (iv) decreases with private health expenditure,  $\phi_i(a, t)p(t)(h_i(a, t) + e(S_i(a, t)))$ , where  $p(t)$  denotes the price for health care, where  $\phi_i(a, t)$  denotes an  $(a, t, i)$ -specific rate of coinsurance, as specified in (19) below, and where the total consumption of health care amounts to the sum of elective health care,  $h_i(a, t)$ , and emergency care,  $e(S_i(a, t))$ ; (v) decreases with an  $(a, t, i)$ -specific tax schedule,  $\tau_i(a, t)$ , as specified in (23) below; (vi) increases with  $(a, t, i)$ -specific social security benefits,  $\pi_i(a, t)$  as specified in (20) below; and (vii) increases with a lump-sum transfer  $s(t)$ , as specified in (24) below, by which the government redistributes accidental bequests across the population. We follow Frankovic et al. (2017) and others by considering a setting without an annuity market.

Note that while the market-wide interest rate,  $r(t)$ , the price for health care,  $p(t)$ , and the lump-sum transfer  $s(t)$ , are identical for both skill groups, their wages are skill-specific,

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<sup>9</sup>We consider skill-independent labour supply  $l(a)$  for lack of data. However, this does not imply a loss of generality, as for the purpose of the present analysis it is sufficient to focus on the pattern of skill-specific earnings  $w_i(t)l(a)$ .

where we would typically expect  $w_s(t) \geq w_u(t)$ , reflecting higher productivity of the skilled. The co-insurance rate, tax-rate and pension benefits are also allowed to vary with the skill level.<sup>10</sup>

### 3.2 Population

Denoting by  $B(t_0)$  the total number of births at time  $t_0$ , we obtain  $N_i^c(a, t) = S_i(a, t)B(t - a)/2$  as the size of the cohort of skill level  $i = s, u$  that was born at time  $t_0 = t - a$  and is alive at age  $a$  and time  $t$ .<sup>11</sup>

By aggregating over age and skills, we obtain the following expressions for the population size (total and by skill group), aggregate capital stock, aggregate effective labour supply (total and by skill group), aggregate consumption (of final goods) and aggregate

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<sup>10</sup>To summarise the individual problem in a nutshell: The individual's choice variables are (i) elective health care,  $h_i(a, t)$ , affecting mortality,  $m(h_i(a, t), M_i(t))$ , and in turn survival,  $S_i(a, t)$ , depending on the exogenous state of medical technology, as captured by the parametric function  $M_i(t)$ ; and (ii) consumption,  $c_i(a, t)$ , affecting period utility,  $u(c_i(a, t))$ . Survival, in turn, determines emergency health care,  $e(S_i(a, t))$ , and both survival and period utility determine life-cycle utility. All prices are given for the individual, as are taxes, social security transfers, health insurance coverage and accidental bequests.

<sup>11</sup>We realise that the assumption of an equal distribution of births across skill-groups is artificial. However, as we will argue in Section 5.1 in greater detail, the 50-50 split of the population implies by construction that relative group size is immaterial. It is sufficient then to focus on a representative individual from each of the skill-groups. We need to keep track, however, of the total population size in order to arrive at a realistic age-structure of the population.

(consumption of) health care (total and by skill group):<sup>12</sup>

$$N(t) = N_s(t) + N_u(t) \quad \text{with} \quad N_i(t) = \int_0^\omega N_i^c(a, t) da \quad i = s, u, \quad (8)$$

$$L(t) = L_s(t) + L_u(t) \quad \text{with} \quad L_i(t) = \int_0^\omega l_i(a) N_i^c(a, t) da \quad i = s, u, \quad (9)$$

$$K(t) = \int_0^\omega [k_s(a, t) N_s^c(a, t) + k_u(a, t) N_u^c(a, t)] da, \quad (10)$$

$$C(t) = \int_0^\omega [c_s(a, t) N_s^c(a, t) + c_u(a, t) N_u^c(a, t)] da, \quad (11)$$

$$H(t) = H_s(t) + H_u(t) \quad \text{with} \quad H_i(t) = \int_0^\omega [h_i(a, t) + e(S_i(a, t))] N_i^c(a, t) da \quad i = s, u. \quad (12)$$

We assume that births grow exogenously at the rate  $\nu$  such that

$$B(t) = B_0 \exp^{\nu t}, \quad B_0 > 0.$$

### 3.3 Production

The economy consists of a manufacturing sector and a health care sector. In the manufacturing sector a final good is produced by employment of capital,  $K^Y$ , as well as skilled and unskilled labour,  $L_s^Y$  and  $L_u^Y$ , respectively. Assuming a neo-classical Cobb-Douglas production function

$$Y(A^Y, K^Y, L_s^Y, L_u^Y) = A^Y (K^Y)^{\alpha_K} (L_s^Y)^{\alpha_s} (L_u^Y)^{\alpha_u}, \quad (13)$$

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<sup>12</sup>Note that all aggregate variables are shaped by the (equilibrium) patterns of health care (by skill and age), which through the survival function determine the age-structure of the population, as measured by the cohort sizes  $N_i^c(a, t)$ . Furthermore, the capital stock,  $K(t)$ , and aggregate consumption,  $C(t)$ , reflect the age-skill patterns of savings and individual consumption, while aggregate health care expenditure,  $H(t)$ , reflect the age-skill patterns of elective and emergency health care.

with  $\alpha_K + \alpha_s + \alpha_u = 1$  and with  $A^Y$  denoting total factor productivity, we can write profit in the manufacturing sector as

$$V^Y = Y(A^Y, K^Y, L_s^Y, L_u^Y) - w_s L_s^Y - w_u L_u^Y - [\delta + r] K^Y, \quad (14)$$

with  $\delta \geq 0$  denoting the rate of capital depreciation. Intuitively, and in line with evidence on the wage patterns (e.g. Acemoglu and Autor 2011), we have  $\alpha_s \geq \alpha_u$ . Indeed, we will assume in Section 5.1 that in line with skill-biased technical progress the factor shares change over time such that  $\dot{\alpha}_s > \dot{\alpha}_u$ .<sup>13</sup>

In analogy to final goods production, we assume that health care is produced by employment of capital,  $K^H$ , as well as skilled and unskilled labour,  $L_s^H$  and  $L_u^H$ , respectively. Again, we assume the production of health care to follow a neo-classical Cobb-Douglas function

$$F(A^H, K^H, L_s^H, L_u^H) = A^H (K^H)^{\beta_K} (L_s^H)^{\beta_s} (L_u^H)^{\beta_u}, \quad (15)$$

with  $\beta_K + \beta_s + \beta_u = 1$  and with  $A^H$  denoting total factor productivity, and obtain profits

$$V^H = pF(A^H, K^H, L_s^H, L_u^H) - w_s L_s^H - w_u L_u^H - [\delta + r] K^H \quad (16)$$

where  $p$  is the price for health care. Note that  $V^Y = V^H = 0$  in a perfectly competitive equilibrium. Again, we assume  $\beta_s \geq \beta_u$  and  $\dot{\beta}_s > \dot{\beta}_u$ .

We allow the factor elasticities in the health care sector to differ from those in final goods production, where in line with evidence in Acemoglu and Guerrieri (2008) we assume  $\beta_K < \alpha_K$ , implying that the health care sector is less capital intensive. We also allow for

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<sup>13</sup>The Cobb-Douglas specification in (13) amounts to the special case of the typical CES formulation with a unitary elasticity of substitution between skilled and unskilled labour (see e.g. Acemoglu and Autor 2011). The focus of the present analysis being on the implications of differential earnings growth for health care rather than the underlying employment changes, we believe this simplification does not greatly bear on our results.

cross-sectoral differences in the labour shares,  $\beta_i \stackrel{\leq}{\geq} \alpha_i$  for  $i = s, u$ , and in total factor productivity,  $A^H \stackrel{\leq}{\geq} A^Y$ .

### 3.4 Health Insurance, Social Security, Taxation, and Accidental Bequests

We consider two forms of health insurance: Medicare, as a public insurance for the population aged 65 and above, and private health insurance for the full population. Medicare pays age-specific but time-uniform co-payments such that  $\phi^{MC}(a) = 0.5$  for  $a \geq 65$  and  $\phi^{MC}(a) = 0$  for  $a < 65$ . These co-payments are financed from a dedicated pay-roll tax at rate  $\tau^{MC}(t)$  such that the budget constraint

$$\tau^{MC}(t) [w_s(t)L_s(t) + w_u(t)L_u(t)] = \frac{p(t)}{2} \int_{65}^{\omega} \left\{ \begin{array}{l} [h_s^*(a, t) + e_s^*(a, t)] N_s^c(a, t) \\ + [h_u^*(a, t) + e_u^*(a, t)] N_u^c(a, t) \end{array} \right\} da \quad (17)$$

with  $h_i^*(a, t) + e_i^*(a, t)$  denoting the equilibrium level of health expenditures for  $(a, t, i)$ , is satisfied at each point in time.<sup>14</sup> Private health insurance at an  $(a, t, i)$ -specific coverage rate  $1 - \phi_i^P(a, t)$  is paid for by  $(a, t, i)$ -specific premiums

$$\tau_i^P(a, t) = [1 - \phi_i^P(a, t)] p(t) [h_i^*(a, t) + e_i^*(a, t)] \quad \forall (a, t, i) \quad (18)$$

such that the insurer breaks even on each individual contract at each point in time. Co-payments at age/year  $(a, t)$  for an individual belonging to group  $i = s, u$  are thus given by

$$\phi_i(a, t) = \phi^{MC}(a) + \phi_i^P(a, t). \quad (19)$$

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<sup>14</sup>For a precise definition, we have  $e_i^*(a, t) := e(S_i^*(a, t))$  with  $S_i^*(a, t) := \exp[-\int_0^a \eta_i(\hat{a}, \hat{t}) m(h_i^*(\hat{a}, \hat{t}), M_i(\hat{t})) d\hat{a}]$ .



Social security benefits are assumed to follow

$$\pi_i(a, t) = \begin{cases} 0 \Leftrightarrow a < 65 \\ \widehat{\pi}_i(t) \geq 0 \Leftrightarrow a \geq 65 \end{cases}, \quad (20)$$

where we assume that all individuals retire fully at age 65, such that

$$l(a) = \begin{cases} \widehat{l}(a) \geq 0 \Leftrightarrow a < 65 \\ 0 \Leftrightarrow a \geq 65 \end{cases}. \quad (21)$$

Social security is assumed to be funded from a dedicated pay-roll tax at rate  $\tau^\pi(t)$  such that the budget constraint

$$\tau^\pi(t) [w_s(t)L_s(t) + w_u(t)L_u(t)] = \int_{65}^{\omega} [\pi_s(t)N_s^c(a, t) + \pi_u(t)N_u^c(a, t)] da \quad (22)$$

is satisfied. Finally, a skill/income-specific labour income tax is raised at rates  $\tau_i^{IT}(t)$ ,  $i = s, u$ , the proceeds of which are used to fund exogenous government expenses  $G(t) > 0$  according to the budget constraint  $\tau_s^{IT}(t)w_s(t)L_s(t) + \tau_u^{IT}(t)w_u(t)L_u(t) = G(t)$ . Thus total tax payments (including private health insurance premia) at age/year  $(a, t)$  for an individual belonging to group  $i = s, u$  are given by

$$\tau_i(a, t) = [\tau^{MC}(t) + \tau^\pi(t) + \tau_i^{IT}(t)] l(a) + \tau_i^P(a, t). \quad (23)$$

Finally, we assume that accidental bequests are redistributed in a lump-sum fashion across the population, such that each individual who is alive at  $t$  receives a transfer

$$s(t) = \frac{\int_0^{\omega} [\mu_s(a, t)k_s(a, t)N_s^c(a, t) + \mu_u(a, t)k_u(a, t)N_u^c(a, t)] da}{N(t)}, \quad (24)$$

with population size  $N(t)$  given by (8). Note that the redistribution of accidental bequests across income groups implies a certain levelling of divergences in wealth. We aim for this specification as the accidental bequests under consideration likely are a poor proxy for systematic differences in inheritances as drivers of a widening inequality in wealth. For robustness, we have also run the model under the assumption that accidental bequests are redistributed within skill groups but have found little quantitative difference.<sup>15</sup>

## 4 Equilibrium Analysis

### 4.1 Life-Cycle Optimum

In Appendix 8.1 we show that the optimal patterns of consumption and elective health care for individuals from group  $i = s, u$  can be described as follows.

For the CES specification of utility in (4), the optimal pattern of consumption is characterised by the Euler equation

$$\frac{c_i(\widehat{a}, t + \widehat{a} - a)}{c_i(a, t)} = \exp \left\{ \int_a^{\widehat{a}} \frac{1}{\sigma} \left[ r(t + \widehat{a} - a) - \rho - \mu_i(\widehat{a}, t + \widehat{a} - a) \right] d\widehat{a} \right\} \quad \forall (a, \widehat{a}, t, i), \quad (25)$$

requiring that the ratio of consumption for any two ages/years  $(\widehat{a}, t + \widehat{a} - a)$  and  $(a, t)$  equals the interest  $r(\cdot)$  net of the effective discount rate  $\rho + \mu_i(\cdot)$ , weighted by the elasticity of intertemporal substitution  $1/\sigma$  and compounded between these ages/years.<sup>16</sup> Importantly, the uninsured mortality risk emerges as an additional factor of discounting in the absence of annuities. Rising mortality then implies a downward drag on consumption towards the end of life. Moreover, differences in mortality across the skill groups, trans-

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<sup>15</sup>More specifically, we find that income from bequests is moderately higher for the skilled if bequests are distributed within skill groups. However, in all cases income from bequests is very small in relation to earnings, implying that the bequest rule plays no role in quantitative terms.

<sup>16</sup>Taking logs and considering the limit  $a \rightarrow \widehat{a}$  it is straightforward to convert (25) into the dynamic representation of the Euler equation  $\frac{c_i(a, t)}{c_i(a, t)} = \frac{1}{\sigma} [r(t) - \rho - \mu_i(a, t)]$ .

late into different patterns of discounting. More specifically, if the unskilled face a greater mortality risk, i.e. if  $\mu_u(\cdot) \geq \mu_s(\cdot)$  for all  $\widehat{a} \in [a, \widehat{a}]$  with a strict inequality for at least one  $\widehat{a}$ , then  $\frac{c_u(\widehat{a}, t + \widehat{a} - a)}{c_u(a, t)} < \frac{c_s(\widehat{a}, t + \widehat{a} - a)}{c_s(a, t)}$ , implying that the unskilled are prone to consume earlier in life and save less.

In order to describe the optimal level of elective health care spending it is helpful to define the value health/survival for an individual of group  $i = s, u$  at age/year  $(a, t)$ , which for the specifications of emergency health care and utility in (3) and (4), respectively, is given by

$$\psi_i(a, t) = \int_a^\omega \left[ \begin{array}{c} \frac{c_i(\widehat{a}, t + \widehat{a} - a)}{1 - \sigma} + c_i(\widehat{a}, t + \widehat{a} - a)^\sigma b \\ + \xi_2 \phi_i(\widehat{a}, t + \widehat{a} - a) p(t + \widehat{a} - a) e(S_i(\widehat{a}, t + \widehat{a} - a)) \end{array} \right] \exp \left[ - \int_a^{\widehat{a}} r(t + \widehat{a} - a) d\widehat{a} \right] d\widehat{a}. \quad (26)$$

The value of an improvement in health/survival at  $(a, t)$  thus amounts to the discounted stream over the expected remaining life-course  $[a, \omega]$  of (i) the monetary value of consumption utility,  $\frac{c_i(\cdot)}{1 - \sigma}$ , (ii) the monetary value of being alive,  $c_i(\cdot)^\sigma b$ , and (iii) the expected cost saving with respect to emergency care expenditures,  $\xi_2 \phi_i(\cdot) p(\cdot) e(\cdot)$ . It is readily checked that the value of health/survival at each  $(a, t)$  increases with the level of the individual's consumption over the remaining life-course, and with the savings on future emergency health care. If their higher income allows the skilled to sustain a higher level of consumption throughout their entire life course, this immediately implies a higher value of health/survival. In addition, if the skilled are facing lower mortality rates, their consumption tends to be shifted towards later stages of the life-course, implying that the wedge in the value of health/survival tends to increase with age. These tendencies are offset, however, if poorer health,  $S_u(\cdot) < S_s(\cdot)$ , exposes the unskilled to higher payments for emergency care,  $e(S_u(\cdot)) > e(S_s(\cdot))$ , which in turn translate into a larger incentive to save such costs.

For the specification of mortality in (1), the optimal level of elective health care for type  $i = s, u$  at age/year  $(a, t)$

$$h_i(a, t) = \frac{M_i(t) \mu_i(a, t) \psi_i(a, t)}{\phi_i(a, t) p(t)} \quad \forall (a, t, i), \quad (27)$$

is then (implicitly) determined by the value of elective health care,  $M_i(t) \mu_i(a, t) \psi_i(a, t)$ , divided by its consumer price,  $\phi_i(a, t) p(t)$ .<sup>17</sup> The value of elective health care, in turn, is given by the individual's value of health/survival,  $\psi_i(a, t)$  weighted by a factor  $M_i(t) \mu_i(a, t)$  representing the effectiveness of health care, as measured by the elasticity  $M_i(t)$ , and the need for health care, as measured by the current mortality rate  $\mu_i(a, t)$ .

Skilled individuals tend to demand a higher volume of elective health care,  $h_s(a, t) > h_u(a, t)$ , as they attach a higher value to health/survival,  $\psi_s(a, t) > \psi_u(a, t)$ , as they have access to more effective health care,  $M_s(t) > M_u(t)$ , and as they enjoy a higher level of health insurance coverage [see Capatina (2015) for the US], such that  $\phi_s(a, t) < \phi_u(a, t)$ . These tendencies are offset to the extent that the skilled face a lower mortality,  $\mu_s(a, t) < \mu_u(a, t)$ . Note, however, that higher emergency spending may expose the unskilled to similar or even greater total expenditure on health care.

## 4.2 General Equilibrium

Referring the reader to a more rigorous characterisation of the general equilibrium in Appendices 8.2 and 8.3 we restrain ourselves here to a brief intuitive description. Perfectly competitive firms in the two sectors  $j = Y, H$  choose capital,  $\widehat{K}^j(t)$ , and the two types of labour,  $\widehat{L}_i^j(t)$  with  $i = s, u$ , so as to maximise their respective period profit (14) and (16). The six first-order conditions determine the six (sector-specific) factor demand functions,

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<sup>17</sup>This condition is equivalent to the condition  $\psi_i(a, t) = -\phi_i(a, t) p(t) / m_h(\cdot)$ , requiring that the value of health and survival equals the effective price of survival, as given by the effective consumer price  $\phi_i(a, t) p(t)$  weighted by  $-1/m_h(\cdot)$ , which is the volume of health care required to lower mortality by one unit.

depending on the set of prices  $\{r(t), w_s(t), w_u(t), p(t)\}$ .<sup>18</sup> Likewise, we obtain the age- and skill-specific demand for consumption goods,  $c_i(a, t)$ , and health care,  $h_i(a, t)$ , from the sets of first-order conditions (25) and (27) of the individual life-cycle problem. The age profiles of individual wealth,  $k_i(a, t)$ , then follow implicitly from the life-cycle budget constraint (7). Aggregating across age-skill-groups at each point in time  $t$  according to (10)-(12) gives us the aggregate supply of capital,  $K(t)$ , and the two types of labour,  $L_i(t)$  with,  $i = s, u$ , as well as the aggregate demand for consumption  $C(t)$  and health care  $H(t)$ .

The general equilibrium characterisation of the economy is completed by the set of five market clearing conditions

$$\begin{aligned}\widehat{L}_s^H(t) + \widehat{L}_s^Y(t) &= L_s(t) \\ \widehat{L}_u^H(t) + \widehat{L}_u^Y(t) &= L_u(t) \\ \widehat{K}^Y(t) + \widehat{K}^H(t) &= K(t) \\ Y(A^Y(t), \widehat{K}^Y(t), \widehat{L}_s^Y(t), \widehat{L}_u^Y(t)) &= C(t) + \dot{K}(t) + \delta K(t) \\ F(A^H(t), \widehat{K}^H(t), \widehat{L}_s^H(t), \widehat{L}_u^H(t)) &= H(t)\end{aligned}$$

corresponding to the skill-specific labour markets, the capital market, the market for final goods and the market for health care, respectively. From these, we obtain a set of four equilibrium prices  $\{r^*(t), w_s^*(t), w_u^*(t), p^*(t)\}$  and the level of net capital accumulation  $\dot{K}(t)$ . Appendix 8.3 derives equilibrium prices and quantities based on the Cobb-Douglas production functions specified in (13) and (15), respectively.

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<sup>18</sup>An interior allocation is guaranteed (i) by the Inada conditions being satisfied by Cobb-Douglas function, and (ii) by a single constraint on the supply of unskilled labour (see Appendix 8.3).

## 5 Numerical Analysis

### 5.1 Calibration Strategy

In the following, we solve the model outlined in the previous section by means of a numerical simulation. For this purpose, we calibrate the model to reflect the development of the US economy over the 55-year time span 1960-2015, capturing the evolution of income and life-expectancy among rich and poor individuals as well as the growth of average health care expenditures, medical technology and the price for medical care. While we assume general equilibrium, we do not impose balanced growth assumptions but rather consider the economy's development over the time span 1960-2015 as a transition path between two steady states, lying outside the time frame under consideration.<sup>19</sup>

In order to study the various drivers of differential longevity growth, we first introduce exogenous time trends to the skill-specific labour shares in a way that replicates the evolution of the income distribution. As the labour share of the skilled group grows at the expense of the unskilled, the skilled (unskilled) group's per-capita yearly income matches the evolution of mean income among the top (bottom) 50% of the income distribution, as found in the data. We then apply average federal tax-rates such that we obtain realistic after-tax income growth within each group. Hence, our model incorporates the increasing income inequality in the US over the last decades, as driven by skill-biased technological change.

Second, we introduce exogenous medical progress that increases the effectiveness of medical care in our model economy. Here, we assume for the unskilled relative to the skilled a lag of 8 years in the access to the state-of-the art medical technology. This lag increases the life-expectancy gap between the skill groups to a realistic level and contributes to a widening of the gap over time.

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<sup>19</sup>More details on the simulation can be found in the final paragraph of Appendix 8.4.

Third, following Capatina (2015) we consider skill-related differences in health-insurance coverage. The unskilled are subject to a slightly lower degree of coverage, exposing them to a higher consumer price of health care.

Fourth, in line with a considerable body of evidence (see Sheiner and Malinovskaya 2016) we assume slower productivity growth in the health care sector as opposed to final goods production. In line with Baumol (1967), this implies that the health care sector absorbs an increasing share of labour, while at the same time the price of health care increases endogenously.

Due to these four factors that govern the access of the two skill/income groups to effective health care, life-expectancy among the skilled/rich and unskilled/poor diverges endogenously in the model. The diverging life-expectancies match quite well recent data on the development of life-expectancy by income strata as provided by Chetty et al. (2016). The model thus offers an economic rationale for the trends observed. Given the finding by Cutler et al. (2011) that changes in behavioural patterns have contributed relatively little to the progression of the life-expectancy gap, we conjecture that a large part of the trend can, indeed, be explained by differential access to health care. Our analysis will allow us to assess the contribution of each of the four channels. Further details on the calibration and data we employ are provided in the following, a technical description of the numerical solution method is provided in Appendix 8.4.

## Demography

Individuals enter the model economy at age 20 and can reach a maximum age of 100 with model time progressing in single years.<sup>20</sup> In our model, a "birth" at age 20 implies a maximum age  $\omega = 80$ . Population dynamics are partly endogenous due to mortality that is determined within the model and partly exogenous due to a growth of "births" at the

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<sup>20</sup>We follow the bulk of the literature and neglect life-cycle decisions during childhood.

fixed rate  $\nu = 0.017$ , which together with the underlying survival process generates a share of the population 65+ and of the aggregate labour force participation that is roughly in line with the data.<sup>21</sup> An in-depth description for our modelling of mortality and survival is provided further on below.

Note that the size of the skilled and unskilled group does not change over time and the overall population grows at a constant rate. This assumption is reflecting our choice of the skilled (unskilled) group to represent the 50% of population with top (bottom) earnings at each point in time. While this obviously amounts to an approximation of unobserved skills (or education) through income, we believe this to be legitimate in the light of observational equivalence in our data. We should also stress that we understand skilled/rich and unskilled/poor individuals to be representatives of their respective groups. Thus, we cannot - and for reasons of modelling clarity - do not wish to model the transition of individuals between the high and low income groups.

## Income

Data on the market income evolution of the rich and poor in our model is based on the evolution of mean income within the top and bottom 50% of the households in the US, as provided by the United States Census Bureau, Table H-3.<sup>22</sup> Since after-tax income is the decisive variable in the spending decisions of households, we also match the after-tax income evolution of the two groups in our model with the respective trends for the top and bottom 50% of households. For this purpose, we employ data from Congressional Budget Office (2016) on the mean market income and after-tax income of households in quintiles

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<sup>21</sup>Our model generates a share of the population 65+ of 13.3% and 17.7% for 1960 and 2010, respectively. Following US census data (adjusted to refer to the population without individuals aged less than 20) the corresponding empirical targets are 14.8 % (1960) and 17.7 % (2010).

<sup>22</sup>The Table H-3 "Mean Household Income Received by Each Fifth and Top 5 Percent" is available at <https://www.census.gov/data/tables/time-series/demo/income-poverty/historical-income-households.html>. We approximate the top (bottom) 50 % mean income by the average of mean incomes among the top (bottom) three fifths, where the third fifth receives only half the weight in each of our two groups.



for the year 2013. Since the same publication shows that market-income and after-tax income inequality among US households has not diverged to any great extent over the last decades, we use the 2013 ratio of after-tax to market income of the top and bottom 50% to obtain average tax rates for each group, namely 22.7% for the top income group and 8.7% for the bottom income group. We then introduce these figures as exogenous labour income tax rates on each group separately and obtain a realistic evolution of after-tax income inequality in the model. For the lack of better data, we assume that the age-specific labour supply does not differ between skill groups and is constant over the whole time horizon (while wages increase). We then proxy the effective labour supply of both age groups by an age-specific income schedule taken from Frankovic et al. (2017).

### **Life-expectancy, Mortality, Medical Progress and Emergency Expenditure**

Average life-expectancy among individuals from the top and bottom 50% income groups are taken from Chetty et al. (2016).<sup>23</sup> The data series is limited to the years 2001 through 2014. However, by applying the calibration procedure described shortly to mortality data from the Human Mortality Database we are able to trace the group specific life-expectancy back to earlier years.

We begin by noting that, based on (1) and (2), the force of mortality,  $\mu_i(a, t)$ , is endogenously determined in the model and depends on health care,  $h_i(a, t)$ , as a decision variable, on the access to the newest medical technology,  $M_i(t)$ , and on the exogenous shifter  $\eta_i(a, t)$ . We then calibrate the parametric components of (2) as follows.

First, we fix the exogenous skill-gradient in mortality that is unrelated to health care by employing the evidence by Cutler et al. (2011) that  $\eta_s(a, t)/\eta_u(a, t) \approx 0.9$  at all times and for all age groups.<sup>24</sup> In order to capture the age-component of  $\eta_i(a, t)$ , we

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<sup>23</sup>We use Table 2 from the accompanying website at <https://healthinequality.org/data/>. Life-expectancy is given disaggregated to sex and hundred income percentiles. We aggregate the data to obtain average life-expectancy among the top and bottom 50% of income distribution.

<sup>24</sup>We obtain the ratio  $\eta_s(a, t)/\eta_u(a, t) \approx 0.9$  from Table 4 in Cutler et al. (2011) as follows. Here, the

consider the year 1980 and find the pattern for  $\eta_s(a, 1980)$  that together with  $\eta_u(a, 1980) = \eta_s(a, 1980)/0.9$  generates age-specific mortality rates for the US that match the data in the Human Mortality Database. Following the evidence in Ford et al. (2006) that around 50% of the decline in (coronary) mortality can be attributed to medical care, we fit a time trend to  $\eta_s(a, t)$  that, again under preservation of the relationship  $\eta_u(a, t) = \eta_s(a, t)/0.9$ , explains 50% of the decline in average mortality over the time span 1960-2015.<sup>25</sup> The implied schedules of  $\eta_i(a, t)$  are combined with the initial income gap in 1960 to determine the initial life-expectancy gap in the model.

Second, and turning to the part of mortality that is amenable to health care, we choose the elasticity of mortality with respect to health care utilisation,  $m_h h/m = -M$ , in the range of  $-0.1$  to  $-0.25$  for both skill groups, which over the time frame 1960-2015 are in line with the estimated elasticities reported in Hall and Jones (2007).

Third, we choose a growth trend to medical effectiveness such that together with the spending elasticities and the exogenous component to mortality explain the joint evolution of health care expenditure per capita and longevity averaged across both skill groups.

Fourth, we assume that medical effectiveness for the unskilled lags behind the respective value for the skilled. We choose a lag of 8 years which, in the presence of medical progress and the skill-specific patterns for health care, increases the life-expectancy gap to a magnitude in line with the data.<sup>26</sup> Thus, we set  $M_u(t) = M_s(t - 8)$ . Assuming  $M_s(t)$

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relative risk figures for Model A reflect the unconditional mortality ratio  $\hat{\mu}_{uc}(t) := \mu_s(t)/\mu_u(t)$ , whereas the figures for Model B reflect relative mortality conditioned on behaviours. Denoting this ratio by  $\hat{\mu}_c(t)$ , assuming that the ratio  $\eta_s(a, t)/\eta_u(a, t)$  predominantly reflects behavioural differences, neglecting the age component and employing the identity  $\hat{\mu}_{uc}(t) = \hat{\mu}_c(t) [\eta_s(t)/\eta_u(t)]$  gives us  $\eta_s(t)/\eta_u(t) = \hat{\mu}_{uc}(t)/\hat{\mu}_c(t)$ . According to column (1) in Table 4 (Cutler et al. 2011), reflecting data from 1971-1975, we have  $\hat{\mu}_{uc}(t) = 0.78$  and  $\hat{\mu}_c(t) = 0.88$  so that  $\eta_s(a, t)/\eta_u(a, t) = 0.89$ . Similar values obtain for columns (2)-(6), with  $\eta_s(a, t)/\eta_u(a, t) = 0.9$  being well in the middle of the range.

<sup>25</sup>We were unable to retrieve evidence on the role of behavioural factors as opposed to medical care for other diseases than coronary heart disease. We thus assume the findings by Ford et al. (2006) to be representative.

<sup>26</sup>Lags by socio-economic status in the diffusion/uptake of state-of-the art medical procedures have been reported for a number of conditions and health care settings (e.g. Skinner and Zhou 2004, Korda et al. 2011, Wang et al. 2012, Hagen et al. 2015, Clouston et al. 2017) with some notable exceptions (Goldman

to reflect the state-of-the-art medical technology, we impose a growth trend on  $M_s(t)$  that together with the lagged  $M_u(t)$  is consistent with the growth of the life-expectancy in the data for the two skill-groups.

Note, however, that changing the path of the frontier technology  $M_s(t)$  for a given  $\eta_i(a, t)$  will change the share of mortality decline that is attributable to health care. Thus, our initial calibration of  $\eta_i(a, t)$  (chosen to match a 50% share) needs to be redone for the new path of  $M_s(t)$ . Vice versa, changing the calibration of  $\eta_i(a, t)$  will require adjusting the path of  $M_s(t)$  to obtain the empirical evolution of life-expectancy. For this reason, we apply the calibration strategy iteratively until both the share of mortality reductions attributable to health care as well as the life-expectancy evolution across groups match their empirical targets.

Finally, we assume that the parameters in (3), describing the functional form for emergency health care, are given by  $\xi_1 = 0.3$  and  $\xi_2 = 0.1$  in our calibration.<sup>27</sup>

## Utility

For the instantaneous utility function in (4), we choose the inverse of the elasticity of intertemporal substitution to be  $\sigma = 1.125$ , which is within the range of the empirically consistent values identified by Chetty (2006). Setting  $b = 9$  then guarantees that  $u(c_i(a, t)) \geq 0$  for all  $(a, t, i)$  and generates an average VOL that lies within the range of plausible estimates, as suggested in Viscusi and Aldy (2003).<sup>28</sup> Moreover, we assume a rate of time preference  $\rho = 0.02$ .

Finally, following Frankovic and Kuhn (2018) we impose a minimum consumption level and Smith 2005). Most of these studies find that these lags translate into mortality differences, again with some exceptions (Hagen et al. 2015).

<sup>27</sup>While we were unable to identify direct evidence to inform our calibration of  $\xi_1$  and  $\xi_2$  we chose the values in a way that generates a plausible pattern of health expenditures across the skill groups. Not adjusting health expenditure for health status through the dependency in (3) would generate much too high an expenditure gap in favour of the skilled.

<sup>28</sup>The model yields a value of life of approx. 4 million USD for skilled and 1.5 million USD for unskilled individuals.

Table 1: Insurance share of health expenditures

|   | Top 50%   |           | Bottom 50% |           |
|---|-----------|-----------|------------|-----------|
|   | 1996-2002 | 2003-2010 | 1996-2002  | 2003-2010 |
| Employer-based insurance, during working life | 0.651     | 0.637     | 0.588      | 0.546     |
| Employer-based insurance during retirement    | 0.141     | 0.126     | 0.111      | 0.093     |
| Medicare                                      | 0.5       | 0.5       | 0.5        | 0.5       |
| Total Retirement                              | 0.641     | 0.626     | 0.611      | 0.593     |

equal to the social security benefit (of the bottom 50%) at a given point in time. We do so in order to avoid negative asset holdings at old age, as would otherwise result from ex-ante optimisation.<sup>29</sup> Given that retirees cannot usually borrow against pension income and given that individuals are downspending their assets in old age (as they do within our model) the minimum consumption constraint is plausible.

### Health Insurance, Social Security and Taxation

We follow Capatina (2015) with respect to the calibration of insurance coverage. She reports average co-payment shares for individuals with (skilled) and without (unskilled) college education over the time frames 1996-2002 and 2003-2010, respectively. Table 1 provides an overview of average health expenditure shares paid for by various insurance programs. The Medicare tax rate  $\tau^{MC}(t)$  and the private health insurance premium  $\tau_i^P(a, t)$  are then determined in equilibrium according to the budget constraints (17) and (18), respectively.

Individuals aged 65 or above receive Social Security (SS) benefits financed by a payroll-

<sup>29</sup>Individuals choose old-age consumption at the beginning of their life, attaching a low probability to reaching very high ages. Consumption allocated to these ages (in the absence of a minimum consumption level) is thus very low and can fall below the social security income, such that it is optimal to pay back debt (accumulated to finance consumption at earlier ages) at very high ages with excess social security income.

tax levied on working individuals. We use data from the EBRI Databook on Employee Benefits<sup>30</sup> that report average SS income for five income quintiles for those aged 65 and higher from 1976 to 2012. From this, we construct average SS income for the top and bottom income group following the same method as for market income. The data indicates that SS income for the bottom 50% has increased from 6400 (2012 constant) USD in 1976 to 9400 USD in 2012, whereas SS benefits for the top 50% have risen from 13600 USD to 14650 USD. In the model, total social security outlays are fully financed by a payroll tax levied uniformly on all workers at a given point in time. The payroll tax  $\tau^\pi(t)$  is calculated according to the budget constraint (22) and amounts to 5.2% in 1975 and 8.6% in 2015.

Finally, we set the income tax rates  $\tau_s^{IT}(t) = 0.227$  and  $\tau_u^{IT}(t) = 0.087$  to match the US after-tax earnings distribution in the year 2013.

## Production Technology and Productivity Growth

Following Acemoglu and Guerrieri (2008), we set the capital share in final goods production and in the health care sector to  $\alpha_K = 1/3$  and  $\beta_K = 1/5$  and keep these values constant for all times.<sup>31</sup> In contrast, we assume time-dependent factor shares for skilled and unskilled labour and set their values as follows. For  $t \leq 1960$ , we set  $\alpha_s(t) = 1/2$  for the final goods sector and  $\beta_s(t) = 3/5$  for the health care sector. Noting that  $\alpha_u(t) = 1 - \alpha_K - \alpha_s(t)$  and  $\beta_u(t) = 1 - \beta_K - \beta_s(t)$  we obtain  $\alpha_u(t) = 1/6$  and  $\beta_u(t) = 1/5$  for  $t \leq 1960$ , respectively. Hence, the labour share in each sector is divided in a way, that three quarters of labour income go towards the skilled workers. This generates a ratio of skilled vs. unskilled earnings in line with the US earnings data.

We then scale  $A^Y(t \leq 1960)$  such that the absolute values of earnings match the targeted

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<sup>30</sup>The complete Databook is available at <https://www.ebri.org/publications/books/index.cfm?fa=databook>. The data we use is provided in chapter 3.

<sup>31</sup>Acemoglu and Guerrieri (2008) refer to the US NAICS classification category 62 "Health care and social assistance", which includes ambulatory health care services (621); hospitals (622); nursing and residential care facilities (623); and social assistance (624) as reported by the Bureau of labour Statistics.

values in  $t = 1960$ . In order to match the evolution of the absolute value of skilled earnings and the ratio between skilled and unskilled earnings after 1960, we choose an appropriate growth rate for  $A^Y(t)$  as well as for  $\alpha_s(t)$  and  $\beta_s(t)$ , assuming that they preserve the (initial) ratio  $\alpha_s(1960)/\beta_s(1960) = 5/6$ . This calibration strategy yields a growth rate of 0.7% for  $A^Y(t)$  and an increase of  $\alpha_s(t)$  and  $\beta_s(t)$  by 10% over 50 years up until  $t = 2010$ , such that  $\alpha_s(2010) = 0.55$  and  $\beta_s(2010) = 0.66$ .

According to equation (44) in Appendix 8.3, the evolution of the price of health care is determined by the growth rate of  $A^H(t)$  together with the evolution of the interest rate, as well as the skilled and unskilled wage rate. The latter two being targeted to replicate the data on after-tax earnings, we choose the growth rate of  $A^H(t)$  to be  $-1\%$ , as this value induces  $p(t)$  to grow over time in accordance with data by the Bureau of Economic Analysis on the growth of medical prices relative to the overall CPI.<sup>32, 33</sup> The interest rate is endogenously determined and evaluates at  $r(t) = 0.040$  in 1975 and  $r(t) = 0.027$  in 2015. The decline in the interest rate is due to population ageing and a subsequent increase in average savings across the population.

## Overview of Functional Forms and Parameters

Table 2 summarises the most important parameters we are employing.

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<sup>32</sup>Again, we calibrate iteratively: changes in  $A^Y(t)$  and  $A^H(t)$  will affect not only  $p(t)$  but also  $r(t)$ , which in turn feeds back into  $p(t)$ , implying we have to readjust  $A^Y(t)$  and  $A^H(t)$  until we find a pattern consistent with the data.

<sup>33</sup>Note that negative productivity growth in the US health care sector (in terms of non-quality adjusted output) at around  $-1\%$  is consistent with the empirical evidence from recent studies (Triplett and Bosworth 2004; Harper et al. 2010).

| Parameter & Functional Forms | Description                                      |
|------------------------------|--|
| $\omega = 80$                | life span  |
| $t_0 = 1950$                 | entry time of focal cohort                       |
| $\rho = 0.02$                | pure rate of time preference                     |
| $\sigma = 1.125$             | inverse elasticity of intertemporal substitution |
| $\delta = 0.05$              | rate of depreciation                             |
| $\alpha_K = 0.33$            | elasticity of capital in $Y$                     |
| $\beta_K = 0.2$              | elasticity of capital in $F$                     |
| $\xi_1 = 0.3$                | scale of emergency health care function          |
| $\xi_2 = 0.1$                | elasticity in emergency health care function     |

Table 2: Model parameters

## 5.2 Scenarios

In the following, we present five sets of results. To begin with, the benchmark scenario in Section 5.2.1 describes the development of the economy and the resulting inequality in longevity over the time span 1960-2015. Set against this, we study the following counterfactual scenarios. Recalling the three forms of skill-bias in (i) earnings growth, (ii) medical effectiveness, and (iii) health insurance, we first study three counterfactual scenarios in each of which we eliminate one form of skill-bias, assuming the benchmark trend for the remaining two. Thus, in Section 5.2.2 we consider the absence of skill-bias in productivity change and wage growth; in Section 5.2.3 we consider the absence of a lag in the access of the unskilled to the most effective health care; and in Section 5.2.4 we consider the absence of a skill-bias in health insurance coverage.

We amend this analysis by studying a fourth counterfactual in Section 5.2.5, where we assume the price for medical care to be fixed while letting the three forms of skill-bias follow their benchmark trends. This is to gauge whether medical price inflation, which per se is without bias, leads to skill-related differences in access.

Finally, we study in Section 5.3 a counterfactual for which we assume the simultaneous

absence of skill-bias in all three dimensions, leaving medical price inflation to take place as in the benchmark. We employ this "triple" counterfactual to identify the joint contributions of the three dynamic forms of skill-bias in the access to effective health care.

### 5.2.1 Benchmark

As is well known, the US have experienced more than half a decade of growing earnings inequality (Autor et al. 2008, Acemoglu and Autor 2011). In our benchmark, we trace this development over the time span 1960-2015 for the after-tax earnings of the top 50% group as opposed to the bottom 50% group. In terminology of our model, we understand these two groups to be the "skilled" with high earnings as opposed to the "unskilled" with low earnings. Figure 1 plots differential earnings growth in our model against the data. Recall that earnings growth reflects the exogenous trends in the income shares for skilled and unskilled labour,  $\alpha_s(t)$ ,  $\alpha_u(t)$  and  $\beta_s(t)$ ,  $\beta_u(t)$ , respectively.

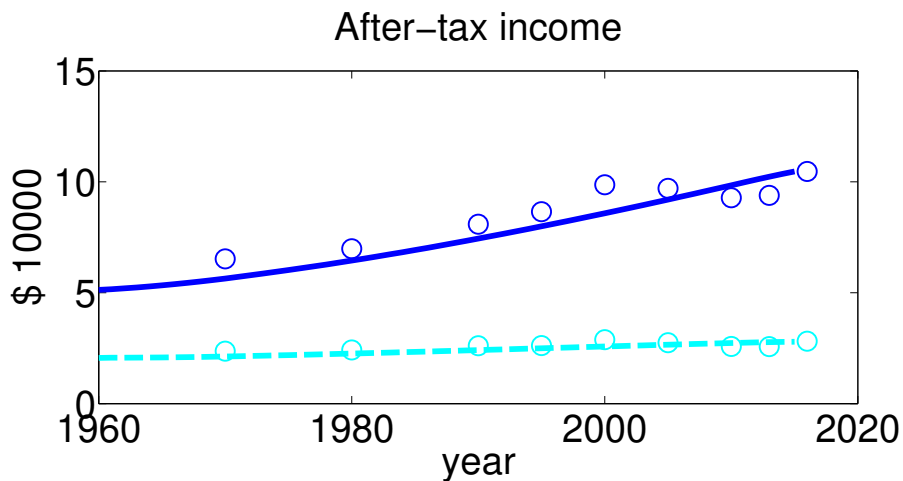


Figure 1: Evolution of after-tax wages for the (skilled) top 50% (blue, solid) and the (unskilled) bottom 50% (cyan, dashed); Circles denote after-tax mean income of the top and bottom 50% as reported by the US census office

Furthermore, we assume medical technology to grow exponentially in a way that the increase in skill-specific life-expectancy in the model matches the data (Figure 2, left panel).



This embraces the lag of 8 years for the unskilled to have access to the most effective health care, implying that  $M_u(t) = M_s(t - 8)$ .

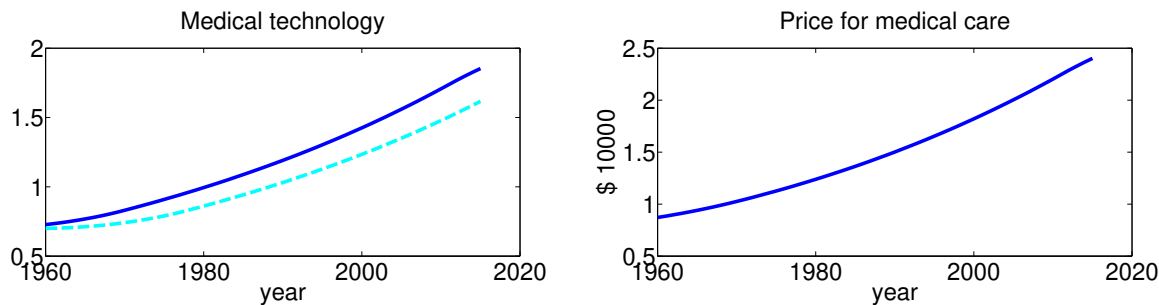


Figure 2: Evolution of the level of medical technology for the skilled,  $M_s(t)$  (blue, solid), and unskilled,  $M_u(t)$  (cyan, dashed); and evolution of the price for medical care  $p(t)$

The third bias in respect to health insurance coverage is reflected in the insurance shares presented in Table 1. While across the two time frames 1996-2002 and 2003-2010 there is a general trend towards a lower share of private health insurance, this is more pronounced for the 50% bottom earners. On average, over 2003-2010 their employer-based insurance coverage during working life amounts to only 85.7% of the coverage enjoyed by the 50% top earners. At 73.8%, the coverage gap for employer-based insurance becomes more pronounced during retirement, but this is largely compensated for by the availability of Medicare.

As Baumol (1967) shows, lagging productivity growth in the health care sector as opposed to final goods production leads to the reallocation of labour into the more labour intensive health care sector as well as to an increase in the wage rate(s). In combination, these effects drive up the price of health care, reflecting the increasing relative cost of producing health care (Figure 2, right panel).<sup>34</sup> Over the time span 1980-2000, medical prices have risen 1.6 times faster than the overall CPI according to the Bureau of Economic Analysis. This compares quite well with the 1.5-fold increase in  $p$  over the same time period

<sup>34</sup>See Acemoglu and Guerrieri (2008) for a thorough analytical treatment of the underlying mechanisms as well as Frankovic et al. (2017) for a discussion how medical progress may lead to similar allocational impacts.

in our benchmark economy.

Due to differential income growth, differential access to the most effective health care, differential health insurance coverage, and possibly due to the increase in the price of health care, the life-expectancy of the top and bottom 50% earners diverges over time, as can be seen in Figure 3.

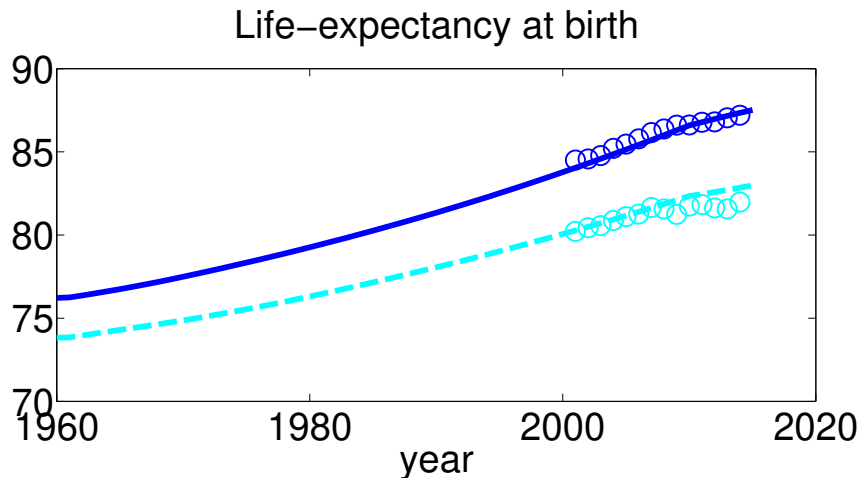


Figure 3: Evolution of life-expectancy for skilled (blue, solid) and unskilled (cyan, dashed)

While life-expectancy increases by some 11.3 years from 76.2 in 1960 to 87.5 in 2015 for the high skilled top earners it increases by only 9.2 years from 73.8 to 83.0 for the low skilled. This amounts to almost a doubling of the life-expectancy gap from 2.4 years in 1960 to 4.5 years in 2015.

Figure 4 plots average health care expenditure,  $p(t) H_i(t) / N_i(t)$  with  $N_i(t)$  and  $H_i(t)$  defined in (8) and (12), respectively, within each skill group  $i = s, u$ . It can be seen that one factor underlying the growing life-expectancy gap is the gradual divergence between the spending paths of the skilled as opposed to the unskilled. Here, the skilled increase their spending at a much higher rate, which is well in line with the complementarity between income growth and medical progress as drivers of health care expenditure (Fonseca et al. 2013; Frankovic and Kuhn 2018).

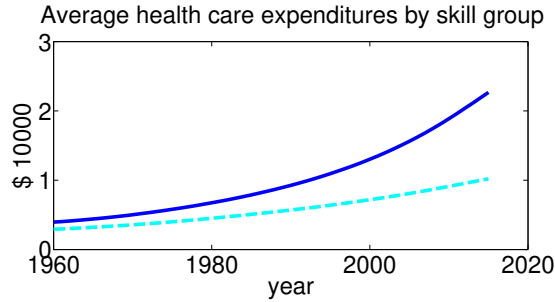


Figure 4: Average health care expenditures for the skilled (blue, solid) and unskilled (cyan, dashed)

### 5.2.2 Counterfactual I: No Skill-bias in Earnings Growth

In the following subsections, the benchmark run will be represented by blue solid graphs, whereas the respective counterfactual experiments will be represented by green, dashed graphs. As a first counterfactual, we consider a set-up where from 1960 onwards there is no skill-bias in earnings growth, in the sense of the income shares for skilled and unskilled labour remaining constant at their 1960 levels over the time span 1960-2015. Technically, this amounts to assuming  $\alpha_s^{cf}(t) \equiv \alpha_s(1960)$  and  $\beta_s^{cf}(t) \equiv \beta_s(1960)$  for all  $t$ . What remains is the initial earnings gap, while medical progress and health insurance continue to be biased in favour of the skilled, as they are in the benchmark scenario.

As can be seen in Figure 5, the discontinuation of skill-biased earnings growth leads to a sizeable "redistribution" of income in favour of the unskilled. While the reduction in earnings growth for the skilled implies an after-tax income in 2015 that is around 10% below its benchmark level, the unskilled receive a significant boost to earnings, leaving them with an after-tax income in 2015 that is around 36% above the benchmark level.

Figure 6 shows that the removal of the skill-bias in earnings growth from 1960 onwards slows down the increase in the health care spending gap. With the skilled spending moderately less and the unskilled moderately more, there is a relative closure in the gap. However, for two reasons this effect is rather limited: First, the unskilled continue to suf-

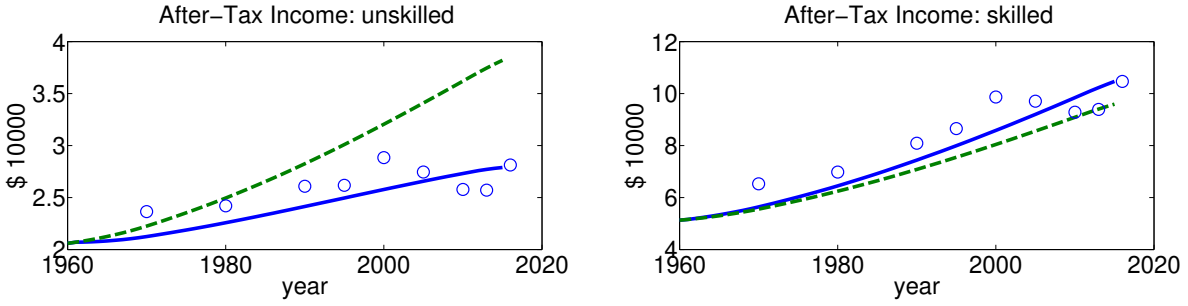


Figure 5: Evolution of earnings for the skilled and unskilled: Benchmark (blue, solid) and counterfactual I (green, dashed)

fer from the initial earnings gap, and, owing to the complementarity between income and medical progress, this translates into a lower incentive to expand health care spending in response to medical progress. Second, the incentive for the unskilled to expand health care spending is curbed by the relatively low effectiveness of the health care they can access, whereas the incentive for the skilled to reduce spending is curbed by the relatively high effectiveness of the health care foregone.

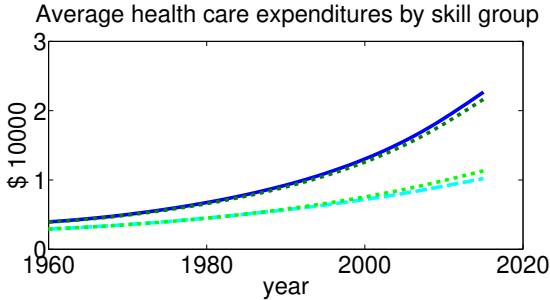


Figure 6: Average health care expenditures for skilled (blue, solid in the benchmark and dark-green, dotted in counterfactual I) and unskilled (cyan, dashed in the benchmark and light-green, dotted in counterfactual I)

This notwithstanding, a counterfactual break on the ongoing divergence of earnings together with the resulting reallocation of health care expenditure would slow down the growth in the longevity gap (calculated as the difference in life expectancy at each point in time) between the skill groups, as is visualised in Figure 7. Absent the continuation of

skill-biased earnings growth from 1960 to 2015, the longevity gap would expand by only 1.7 years instead of 2.1 years.

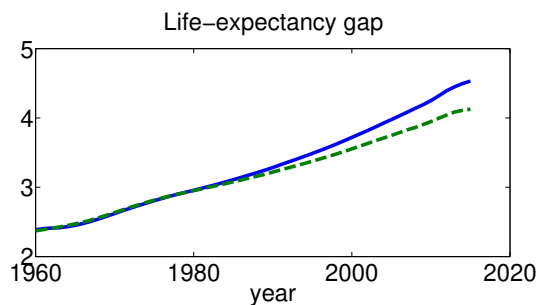


Figure 7: Evolution of life expectancy gap: Benchmark (blue, solid) and counterfactual I (green, dashed)

### 5.2.3 Counterfactual II: No Skill-bias in the Effectiveness of Health Care

This counterfactual explores the role of skill-bias in the access to (or in the use of) state-of-the-art medical technology. The green, dashed plot in the following graphs thus refers to a counterfactual scenario in which there is no lag in the evolution of medical technology available to the unskilled, such that  $M_u^{cf}(t) \equiv M_s(t)$  for the time span 1960-2015. As Figure 8 shows, the immediate access to state-of-the-art medical technology would boost the increase in life-expectancy among the unskilled and would slow down the increase in the longevity gap from 2.1 to only 0.9 years by 2015.

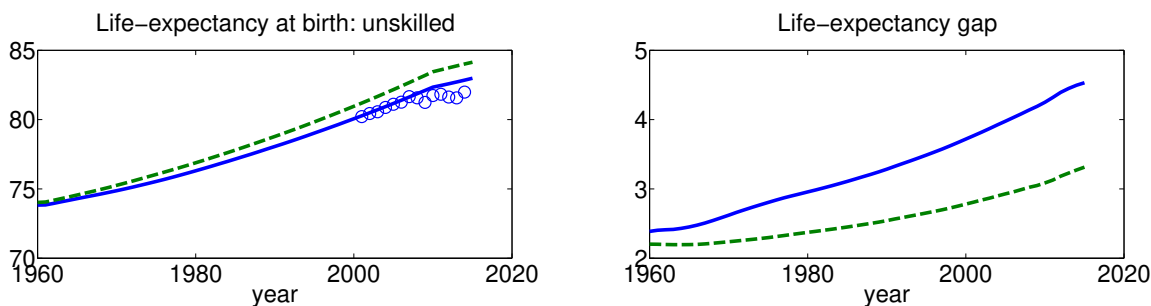


Figure 8: Evolution of life-expectancies and life-expectancy gap: Benchmark (blue, solid) and counterfactual II (green, dashed)

Surprisingly, the immediate access to effective health care does not raise much the average health care spending among the unskilled (see Figure 9).<sup>35</sup> Thus, the counterfactual reduction in the longevity gap is explained by the higher effectiveness of health care utilisation by the unskilled alone.

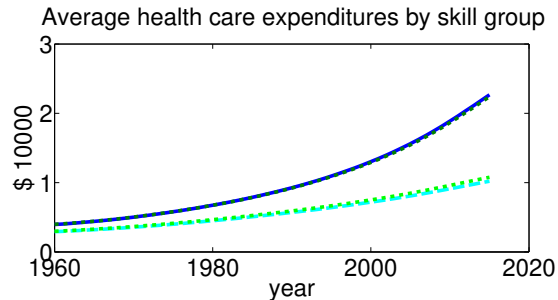


Figure 9: Average health care expenditures for skilled (blue, solid in the benchmark and dark-green, dotted in counterfactual II) and unskilled (cyan, dashed in the benchmark and light-green, dotted in counterfactual II)

#### 5.2.4 Counterfactual III: No Skill-bias in Health Insurance Coverage

Here, we assume that for unskilled individuals co-insurance levels are lowered to those faced by the skilled, such that  $\phi_u^{cf}(a, t) \equiv \phi_s(a, t)$  over the time span 1960-2015. This amounts to an increase in health insurance coverage at the lower end of the income distribution, which to some extent is representing the idea of the 2010 Affordable Care Act (Obama Care). The effects we find are very small, and we therefore abstain from illustrating them graphically. Overall, the life-expectancy gap would be about 0.1 year lower in 2015 in the absence of a skill-bias in health insurance. Given the relatively minor differences in health insurance coverage between the top 50% and bottom 50% income groups (consult Table 1 for the magnitudes involved), this is unsurprising.

We should caution, however, that our focus on two income groups only is likely to obscure much larger effects at the tails of the distribution. In particular, we would expect

<sup>35</sup>At the level of the individual, it can be verified that health care expenditure is deferred to later stages of the life-cycle, but this does not lead to an increase in per capita spending among the unskilled.

a lot of variance in the degree of health insurance coverage within the bottom 50% income group where many individuals within the lowest income strata are lacking health insurance entirely. Opening access to health care for these individuals through the provision of health insurance should yield significant gains in longevity.

### 5.2.5 Counterfactual IV: No Medical Price Inflation

In this counterfactual, we explore whether the inflation in the price for health care, as is induced by productivity growth in the final goods sector, exacerbates inequality in the access to health care and the resulting gap in life-expectancy. One concern may be that the unskilled are doubly punished by not participating in productivity-driven increases in earnings while at the same time being exposed to price inflation in the health care sector. Thus, we consider a counterfactual scenario in which we fix to a constant level the price for health care from 1980 onward, such that  $p^{cf}(t \geq 1980) = p(1980)$ , as is depicted in Figure 10. Note that this implies that from 1980 onward the health care market does not actually clear in the counterfactual.

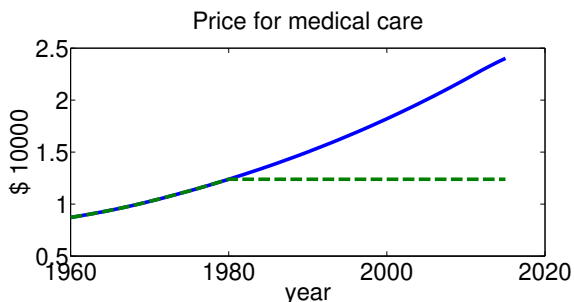


Figure 10: Evolution of the price for medical care: Benchmark (blue, solid) and counterfactual IV (green, dashed)

In the absence of medical price inflation, the average demand for health care rises for both groups relative to the benchmark (see right panel in Figure 11) while average health care expenditures fall within both groups (see left panel in Figure 11). Note that this is consistent with a demand elasticity of health care below one (McGuire 2012). As a

consequence of the greater demand for health care in the absence of medical price inflation, life-expectancy rises for both groups relative to the benchmark (Figure 12) .

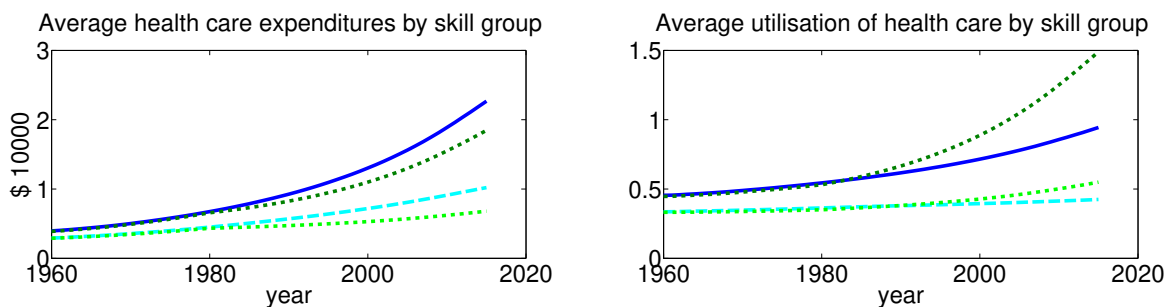


Figure 11: Average health care expenditures  $pH_i/N_i$  and demand  $H_i/N_i$  for the skilled  $i = s$  (blue, solid in the benchmark and dark-green, dotted in counterfactual IV) and unskilled  $i = u$  (cyan, dashed in the benchmark and light-green, dotted in counterfactual IV)

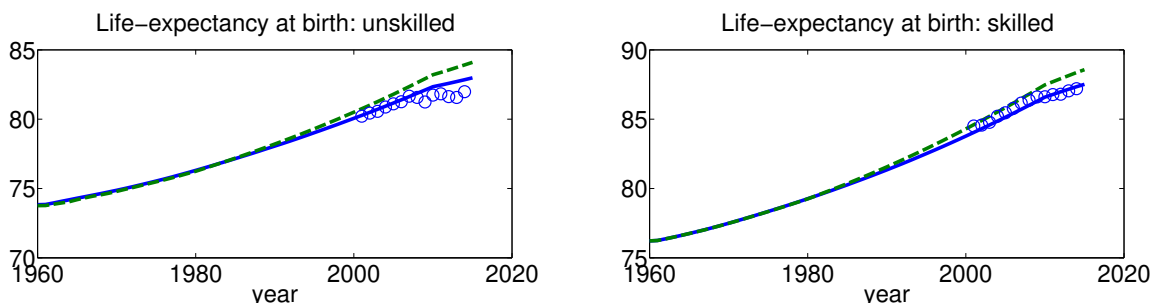


Figure 12: Evolution of life-expectancy: Benchmark (blue, solid) and counterfactual II (green, dashed).

Notably, this has no significant effects on the life-expectancy gap, as seen in Figure 13.

Indeed, in the absence of medical price inflation (from 1980 onward) both groups would face an increase in life expectancy by about 1.25 years in 2015. Thus, while medical price inflation slows down in a substantial way the expansion in life expectancy, it does not increase the gap. As the right panel in Figure 11 shows, medical price inflation curbs the demand for health care for the skilled to a greater extent. In and of itself, this would suggest even a closure in the life expectancy gap, which is (marginally) true. This effect, in turn, however is offset by the fact that due to decreasing returns of health care, the



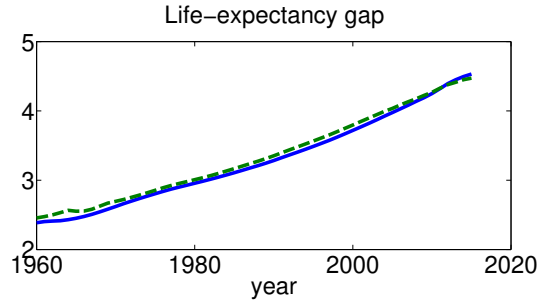


Figure 13: Evolution of life-expectancy gap: Benchmark (blue, solid) and counterfactual IV (green, dashed)

reduction in health care from a lower level leads to a larger increase in mortality for the unskilled.

### 5.3 Explaining the Growth in the Life-expectancy Gap

In order to gauge the contribution of the three forms of skill-bias towards explaining the growth in the life-expectancy gap over the time span 1960-2015 we consider a final counterfactual (V) in which we assume the absence of skill-bias in all three directions, amounting to the combined application of the assumptions for the counterfactual scenarios (I)-(III). For this scenario, we find an increase of 0.5 years in the longevity gap from 2.4 years in 1960 to 2.9 years in 2015.

This implies that about 24% of the 2.1 year increase in the longevity gap in the benchmark scenario remain unexplained by skill-bias. Given the evidence in Cutler et al. (2011) that behavioural changes have contributed little to the increase in the longevity gap and given our finding that medical price inflation has no sizeable impact, the "residual" increase can be attributed to income-related differences in the use of new medical technology and in the gains from it. Although the income gap is assumed not to widen beyond its initial 1960 value, the persistence of a (constant) income gap in itself induces a widening of the longevity gap. This is because the propensity to expend on increasingly effective health care increases at a higher rate for the top earners due to the complementarity between

Table 3: Comparing Benchmark and Counterfactuals (CFs) to identify contribution of biases

| Longevity gap                      | in 2015   | Increase<br>1960-2015 | due to bias | share of benchmark<br>increase explained |
|------------------------------------|-----------|-----------------------|-------------|--|
| Benchmark                          | 4.5 years | 2.1 years             | -           | -  |
| CF I: no skill-bias in earnings    | 4.1 years | 1.7 years             | 0.4 years   | 19 %                                     |
| CF II: no skill-bias in med. eff.  | 3.3 years | 0.9 years             | 1.2 years   | 57 %                                     |
| CF III: no skill-bias in insurance | 4.4 years | 2.0 years             | 0.1 years   | 5 %                                      |
| Sum CF I-III:                      | -         | -                     | 1.7 years   | 81%                                      |
| CF V: CF I-III combined            | 2.9 years | 0.5 years             | -           | 24%                                      |

income and medical progress. Thus, any given gap in income generates more and more diverse outcomes over time, reflecting the lower capacity of the unskilled to participate in the benefits from medical progress.

We conclude by summarizing in Table 3 the contribution of the various channels to the increase in the longevity gap over the time span 1960-2015. We omit medical price inflation [counterfactual (IV)] as it did not generate a sizeable impact.

According to the last column of the table, skill-bias in earnings growth, in the access to state-of-the art medical technology, and in health insurance coverage account for about 19%, 57% and 5%, respectively, of the increase in the longevity gap. Strikingly, about 70% of the combined effects can be attributed to a bias in the lack of access to the newest medical technology. This said, income differences matter not just through their dynamic effect but also through their interaction with (unbiased) medical progress. With 24% of the total increase in the longevity gap being attributable to this channel and, thus, only 76% being attributable to the combination of the three forms of skill-bias, we find that, in sum, the individual biases I-III are "overpredicting" the longevity gap by some 5%.

While this amounts to only a moderate "error", it suggests that complementarities between the different forms of skill-bias do not matter much in explaining the combined effect. This may appear surprising in light of the finding by Fonseca et al. (2013) and Frankovic

and Kuhn (2018) that the complementarity between income, medical progress and health insurance is crucial for explaining the increase in health expenditures. To understand the absence of complementarity across the different biases, it is helpful to realise that complementarities take effect through spending incentives, where e.g. the willingness to spend an additional dollar of income increases with the effectiveness of medical technology. While such a mechanism is, indeed, underlying the dynamics in counterfactual V and counterfactual I; it is absent from counterfactual II on skill-bias in medical effectiveness, where the impact on the longevity gap essentially arises for given spending patterns. At the same time, the effects through counterfactual III on skill-bias in health insurance are quantitatively small. Thus, with two of the three biases unrelated in a quantitatively meaningful way to changes in spending incentives, this shuts down the channel for complementarities to take effect across the skill-biases addressed in I-III.

## 6 Policy Implications and the Role of Medical Progress

Our results suggest that a policy-maker concerned about unequal access to health care should pay particularly close scrutiny to two features of the access to health care, both of which are intricately related to medical progress.

First, it may well be more effective to enable disadvantaged groups to access the most effective forms of health care and use health care effectively than to mitigate a divergent ability of different social groups to pay for health care. Notably the skill-bias in the effectiveness of health care, as measured by  $M_s(t)/M_u(t)-1 = M_s(t)/M_s(t-8)-1 = e^{8g_M}-1$ , increases in the rate of medical progress,  $g_M$ . Thus, while welcome per se, a higher pace of medical progress may well exacerbate the access gap to the disadvantage of the unskilled if they are struggling with catching up. Thus, policies based on the provision of information on the availability and effective use of state-of-the-art diagnosis and treatment

as well as targeted programmes that facilitate the access to advanced and complex hospital care and/or pharmaceutical therapies are likely to prove more effective than a pure redistribution of income. Especially, the introduction of appropriate programmes of managing chronic conditions appears to be important here (e.g. Schoen et al. 2008; Röttger et al. 2017). Stretching beyond health care policies, our results reinforce earlier findings that the provision of universal education that helps individuals to manage their health and overcome access barriers to the health care system (regardless of income) should be instrumental in lowering the longevity gap.

Second, and now turning to the role of income as a determinant of access, even if the widening of the income gap can be stopped, this would not stop the widening of the longevity gap that comes with continued medical progress. Even just to arrest the divergence in longevity, the policy-maker would effectively have to close the income gap. Conversely, while being welcome per se, even unbiased medical progress, such that  $M_s(t)/M_u(t) - 1 = 0$ , is prone to bring about an increasing gap in life-expectancy at least within (private) health care systems with substantial co-payments. Intuitively, income differences do not translate into different demand for health care unless it is sufficiently effective in lowering mortality. The implication is that with a view to maintaining or reducing the longevity gap, increasingly rapid medical progress would need to be accompanied by policy measures that enhance the purchase of health care especially by lower income strata or ensure equal consumption by other means, such as the public provision of health care. In that sense European health care systems with their greater focus on public provision are likely to be more robust against an unequal distribution of the benefits from medical progress.

## 7 Conclusions

We have studied an overlapping generations model in which representatives of two groups, the skilled and the unskilled, purchase health care towards extending their longevity. The unskilled are subject to four disadvantages: they face lower earnings to begin with, they face lower earnings growth due to skill-biased technological change, they face a lag in access to the most effective medical technology, and they benefit less from health insurance. Based on a calibration of the model to reflect the US economy and health care system over the time span 1960-2015 we study the extent to which these four disadvantages explain the emerging longevity gap between the recipients of the top 50% (net) income, tantamount to the skilled in our model, and the recipients of the bottom 50%, tantamount to the unskilled. We find that while all four channels contribute to the emergence of the longevity gap, differences in health insurance coverage and differential earnings growth explain the least of the increase while skill-bias in the access to and use of advanced medical technology plays a very strong part. Notably, however, even in the presence of symmetric access to state-of-the art health care, the skilled are prone to benefit more, and increasingly so, from medical progress than the unskilled. This is owing to the higher propensity of high income earners to spend on health care into which medical progress is "embedded". Due to the complementarity between income and medical progress, this propensity increases over time, driving a growing spending wedge between the skilled and the unskilled. We find that both that the impact of both skill-bias in income and skill-bias in effectiveness tends to be magnified in the presence of medical progress. The risk of the disadvantaged being increasingly left behind in environments with rapid medical change calls for accompanying policies both in regard to incentivising and enabling the disadvantaged to participate in the benefits from medical progress.

While our model offers a first theory-guided perspective on the channels through which

socioeconomic inequality drives inequality in longevity, a number of open issues merit further attention. First, by considering a fixed population that is split into the 50 percent top earners as opposed to the 50 percent bottom earners our current model abstracts from the way in which the income distribution relates to the distribution of skills or education for that matter. We believe this stylisation to be immaterial for our current results as (i) educational choices are not the focus of this analysis; and (ii) the evolution of wages is taken from the data and, as such, reflects the dynamics of the underlying education/skill structure. Our modelling of a population cleanly structured by the 50 % top and bottom earners then has the merit of allowing a clean characterisation of the representative life-cycle allocation within each group and a clean comparison of outcomes across the two groups. It does rule out, however, the study of societal and/or policy changes that lead to changes in the educational distribution. There is an interest in understanding how these changes determine the shape of the income distribution in a richer model in which wages are not just driven by exogenous (biased) productivity growth but also by the size and labour supply of the different skill groups. From a quantitative angle, there is an interest in disaggregating the two groups into finer grained social strata in order to identify the longevity impact of what is likely to be much larger heterogeneity in terms of access barriers to effective health care at the tails of the distribution. Further scope for research lies in an analysis of the extent to which the access to health care is shaped by family background.<sup>36</sup> Chetty et al. (2014) document rather stable patterns of social mobility for the US over time but argue that consequences may be harsher with rising inequality. Böhm et al. (2015) show that the public provision of higher education yields only limited returns to the low skilled. Our analysis suggests that similar arguments are likely to apply in respect to the social gradient in the access to innovative medicine and the resulting health outcomes.

Second, we assume that health only bears on longevity, whereas in reality the feedback

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<sup>36</sup>We are grateful to a reviewer for drawing our attention to this issue.

channel of health on labour supply and, thus, on income is prone to play a role. This is particularly true for the unskilled who typically face health-related restrictions in their labour supply fairly early on in life. Prados (2017) estimates the contribution of health differences to the emergence of earnings inequality over the life-cycle to be around 9 percent. While raising policy issues in its own right, we would consider this feedback to be of comparatively minor importance in respect to the main objective of our paper which was to assess the contribution of (exogenous yet properly calibrated) earnings inequality as opposed to other skill/education-related drivers of the longevity gap.

Third, we have cast our study against a US backdrop, which may raise questions about the extent to which our results extend to European health care systems that typically feature more extensive health insurance coverage or the straight public provision of health care. Better access in financial terms would clearly imply a smaller longevity gap and one that is more prominently driven by direct skill/education-bias in the access to state-of-the-art health care, as documented by Fiva et al. (2014) for Norway, or in the effective use of health care, as documented by Avitabile et al. (2011) for a set of European countries. Strikingly, however, Bago d’Uva and Jones (2009) and Vallejo-Torres and Morris (2013) provide evidence of a positively sloped income gradient in utilisation even in the absence of substantial out-of-pocket payments. To study this issue, one would require a non-trivial extension of the model where the demand for health care is governed by a time cost. A positively rather than negatively sloped income gradient in utilisation would then seem to imply that the income gradient in the valuation of health/survival more than overcompensates the gradient in the time cost associated with the consumption of health care.

Fourth, while our model is relying on market clearance through price adjustments, which we believe to be a reasonable representation of the US health care system, congestion within the health care system may pose direct constraints on access. While we need to

relegate to future research the modelling of congestion as an endogenous gap between the demand for health care and a constrained capacity, we can speculate on its consequences within the setting we are considering. In as far as congestion leads to a uniform increase in the price for health care akin to medical price inflation, this would be detrimental to the survival of both skill groups but without further consequences for the longevity gradient. In as far as congestion is associated with a lower effectiveness of care (due to e.g. waiting times or cuts in the quality of health care) the consequences depend on whether the reduction in effectiveness is symmetric or whether it is biased against one of the skill groups. In the former case, congestion would lower the survival prospects for both skill groups but, in reversal to the impact of medical progress, may effectively reduce the longevity gap. This effect would be offset to the extent that the unskilled are more exposed to the impact of congestion.

Fifth, Chetty et al. (2016) find that the longevity gap is considerably smaller in affluent cities with well-educated populations, such as New York or San Francisco. The authors suggest that one possible reason for this may lie in the presence of neighbourhood effects leading to spillovers from well-educated individuals to the less-educated. These may come in the direct form of informational spillovers through social exchange, but perhaps more so through the provision of better and/or more extensive health care facilities with public good features financed through the higher expenditure of the skilled/well-to-do. Similarly, the higher spending of the skilled/well-to-do may induce R&D into medical innovations which subsequently benefit the unskilled as well (see Frankovic and Kuhn 2018 for a similar argument relating to intergenerational spillovers). Tracing out how policy and institutions are shaping such spillovers constitutes an interesting application of our model.

We relegate extensions along these five lines to future study.



## 8 Appendix

### 8.1 Optimal Solution to the Life-cycle Problem

For notational convenience, we drop the group index  $i$ . The individual's life-cycle problem, i.e. the maximisation of (5) subject to (6) and (7) can be expressed by the Hamiltonian

$$\mathcal{H} = uS - \lambda_S \mu S + \lambda_k (rk + lw - c - \phi p(h + e) - \tau + \pi + s),$$

with  $\lambda_S$  and  $\lambda_k$  denoting the co-states on  $S$  and  $k$ , respectively. We obtain the first-order conditions<sup>37</sup>

$$\mathcal{H}_c = u_c S - \lambda_k = 0, \quad (28)$$

$$\mathcal{H}_h = -\lambda_S \eta m_h S - \lambda_k \phi p = 0, \quad (29)$$

and the adjoint equations

$$\dot{\lambda}_S = (\rho + \mu) \lambda_S - u + \lambda_k \phi p e_S, \quad (30)$$

$$\dot{\lambda}_k = (\rho - r) \lambda_k. \quad (31)$$

Evaluating (28) at two different ages/years  $(a, t)$  and  $(\hat{a}, t + \hat{a} - a)$ , equating the terms, and rearranging gives us

$$\begin{aligned} \frac{u_c(c(\hat{a}, t + \hat{a} - a))}{u_c(c(a, t))} &= \frac{\lambda_k(\hat{a}, t + \hat{a} - a)}{\lambda_k(a, t)} \frac{S(a, t)}{S(\hat{a}, t + \hat{a} - a)} \\ &= \exp \left\{ \int_a^{\hat{a}} \left[ \rho + \mu(\hat{a}, t + \hat{a} - a) - r(t + \hat{a} - a) \right] d\hat{a} \right\}, \quad (32) \end{aligned}$$

where the second equality follows when integrating the adjoint equation (31) to obtain  $\lambda_k$ . Substituting  $u_c(c) = c^{-\sigma}$ , as from (4), and rearranging further, (32) is readily transformed into the Euler equation (25) given in the main body of the paper.

Inserting (28) into (29) allows to rewrite the first-order condition for health care as

$$\frac{\lambda_S}{u_c} = -\frac{\phi p}{\eta m_h}. \quad (33)$$

Integrating (30) we obtain

$$\begin{aligned} \lambda_S(a, t) &= \int_a^\omega [u(c(\cdot)) - u_c(c(\cdot)) \phi(\cdot) p(t + \hat{a} - a) e_S(S(\cdot)) S(\cdot)] \\ &\quad \times \exp \left[ - \int_a^{\hat{a}} \left( \rho + \mu(\hat{a}, t + \hat{a} - a) \right) d\hat{a} \right] d\hat{a}, \end{aligned}$$

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<sup>37</sup>Here,  $u_c$ ,  $m_h$  and  $e_S$  refer to the partial derivatives of the respective functions.

where  $(\cdot) = (\widehat{a}, t + \widehat{a} - a)$ . Using this, we can express the value of health/survival as

$$\begin{aligned} \psi(a, t) &:= \frac{\lambda_S(a, t)}{u_c(a, t)} \\ &= \int_a^\omega \frac{u_c(c(\widehat{a}, t + \widehat{a} - a))}{u_c(c(a, t))} \left[ \frac{u(c(\cdot))}{u_c(c(\cdot))} - \phi(\cdot) p(t + \widehat{a} - a) e_S(S(\cdot)) S(\cdot) \right] \\ &\quad \times \exp \left[ - \int_a^{\widehat{a}} \left( \rho + \mu(\widehat{a}, t + \widehat{a} - a) \right) d\widehat{a} \right] d\widehat{a}. \end{aligned}$$

Inserting from (32); observing from (3) and (4) that  $e_S(S(\cdot)) = \frac{\xi_2 e(S(\cdot))}{S(\cdot)}$  and  $\frac{u(c(\cdot))}{u_c(c(\cdot))} = \frac{c(\cdot)}{1-\sigma} + c(\cdot)^\sigma b$ , respectively; substituting and rearranging appropriately gives (26) in the main body of the paper. Inserting this into (33); observing from (1) and (2) that  $\eta m_h = \frac{\eta M m}{h} = \frac{M \mu}{h}$ ; substituting and rearranging then gives (27) in the main body of the paper.

## 8.2 Characterisation of General Equilibrium

In this Appendix we provide a general characterisation of the general equilibrium, deferring to Appendix 8.3 a more detailed derivation for the case of Cobb-Douglas production functions. For each period  $t$  we have the following unknown variables:

- inputs  $\{K^Y(t), K^H(t), L_s^Y(t), L_u^Y(t), L_s^H(t), L_u^H(t)\}$ ,
- prices  $\{r(t), w_s(t), w_u(t), p(t)\}$ ,
- aggregate demand  $\{C(t), H(t)\}$ ,
- aggregate net saving, equivalent to the change in the capital stock  $\dot{K}(t)$ ,

summing up to 13 variables. These are determined through (we drop the time index for convenience)

- 6 first-order conditions on factor inputs [see (34)-(36) in Appendix 8.3], which give the factor demand functions  $\{\widehat{K}^Y(r, w_s, w_u), \widehat{K}^H(r, w_s, w_u, p), \widehat{L}_s^Y(r, w_s, w_u), \widehat{L}_u^Y(r, w_s, w_u), \widehat{L}_s^H(r, w_s, w_u, p), \widehat{L}_u^H(r, w_s, w_u, p)\}$ , depending on the factor prices and, in case of the health care sector, on the price for health care;
- a set of first-order conditions (25) and (27) for  $a \in [0, \omega]$ , which together with the individual's life-cycle budget constraint (7) determine the  $(a, t, i)$ -specific levels of consumption  $c_i(a, t)$  and elective health care  $h_i(a, t)$ . Aggregation according to (11) and (12) gives the demand for consumption  $C(r, w_s, w_u, p)$  and health care  $H(r, w_s, w_u, p)$ , depending on the four prices;<sup>38</sup>

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<sup>38</sup>Through the life-cycle budget constraint and the individual Euler equation, the demand function  $C(\cdot)$  is also contingent on the expectation about future prices over the remaining life-course. The same applies to the demand function  $H(\cdot)$  for which the future price paths filter in through the value of health/survival.

- 5 market clearing conditions

$$\begin{aligned}
\widehat{K}^Y(r, w_s, w_u) + \widehat{K}^H(r, w_s, w_u, p) &= K, \\
\widehat{L}_s^Y(r, w_s, w_u) + \widehat{L}_s^H(r, w_s, w_u, p) &= L_s, \\
\widehat{L}_u^Y(r, w_s, w_u) + \widehat{L}_u^H(r, w_s, w_u, p) &= L_u \\
F(A^H, \widehat{K}^H(r, w_s, w_u, p), \widehat{L}_s^H(r, w_s, w_u, p), \widehat{L}_u^H(r, w_s, w_u, p)) &= H(r, w_s, w_u, p), \\
Y(A^Y, \widehat{K}^Y(r, w_s, w_u, p), \widehat{L}_s^Y(r, w_s, w_u, p), \widehat{L}_u^Y(r, w_s, w_u, p)) &= C(r, w_s, w_u, p) + \dot{K} + \delta K,
\end{aligned}$$

which determine the set of equilibrium prices  $\{r^*, w_s^*, w_u^*, p^*\}$  and aggregate net saving, as captured by  $\dot{K}$ .

### 8.3 Equilibrium Relationships with Cobb-Douglas Technologies

For reasons of saving space, we omit time indices throughout. Perfectly competitive firms in the production sector choose capital  $K^Y$  and labour  $\{L_s^Y, L_u^Y\}$  so as to maximise period profit (14) subject to the production technology in (13). Likewise, providers of health care choose capital  $K^H$  and labour  $\{L_s^H, L_u^H\}$  so as to maximise period profit (16) subject to (15). From the first-order conditions

$$r + \delta = \frac{\alpha_K Y}{K^Y} = \frac{p\beta_K F}{K^H}, \quad (34)$$

$$w_s = \frac{\alpha_s Y}{L_s^Y} = \frac{p\beta_s F}{L_s^H}, \quad (35)$$

$$w_u = \frac{\alpha_u Y}{L_u^Y} = \frac{p\beta_u F}{L_u^H}, \quad (36)$$

we obtain factor demand as

$$K^Y = \frac{\alpha_K Y}{r + \delta}, \quad L_s^Y = \frac{\alpha_s Y}{w_s}, \quad L_u^Y = \frac{\alpha_u Y}{w_u},$$

and

$$K^H = \frac{\beta_K p F}{r + \delta}, \quad L_s^H = \frac{\beta_s p F}{w_s}, \quad L_u^H = \frac{\beta_u p F}{w_u}, \quad (37)$$

respectively. From this we can calculate the factor intensities

$$k^Y : = \frac{K^Y}{L_u^Y} = \frac{\alpha_K}{\alpha_u} \frac{w_u}{r + \delta}, \quad (38)$$

$$\ell^Y : = \frac{L_s^Y}{L_u^Y} = \frac{\alpha_s}{\alpha_u} \frac{w_u}{w_s}, \quad (39)$$

$$k^H : = \frac{K^H}{L_u^H} = \frac{\beta_K}{\beta_u} \frac{w_u}{r + \delta}, \quad (40)$$

$$\ell^H : = \frac{L_s^H}{L_u^H} = \frac{\beta_s}{\beta_u} \frac{w_u}{w_s}, \quad (41)$$

respectively. Now write

$$w_u = \frac{\alpha_u Y}{L_u^Y} = \alpha_u A^Y (k^Y)^{\alpha_K} (\ell^Y)^{\alpha_s} = \alpha_u A^Y \left( \frac{\alpha_K}{\alpha_u} \frac{w_u}{r + \delta} \right)^{\alpha_K} (\ell^Y)^{\alpha_s}$$

and solve for

$$w_u = \widehat{w}_u(r, \ell^Y) = \alpha_u \left[ A^Y \left( \frac{\alpha_K}{r + \delta} \right)^{\alpha_K} (\ell^Y)^{\alpha_s} \right]^{\frac{1}{1 - \alpha_K}}. \quad (42)$$

We then obtain from (39)

$$w_s = \widehat{w}_s(r, \ell^Y) = \frac{\alpha_s \widehat{w}_u(r, \ell^Y)}{\alpha_u \ell^Y} = \alpha_s \left[ A^Y \left( \frac{\alpha_K}{r + \delta} \right)^{\alpha_K} (\ell^Y)^{-\alpha_u} \right]^{\frac{1}{1 - \alpha_K}}. \quad (43)$$

Inserting from (37) into (15) and solving for  $p$  we obtain

$$p = \widehat{p}(r, \ell^Y) = \frac{1}{A^H} \left( \frac{r + \delta}{\beta_K} \right)^{\beta_K} \left( \frac{\widehat{w}_s(r, \ell^Y)}{\beta_s} \right)^{\beta_s} \left( \frac{\widehat{w}_u(r, \ell^Y)}{\beta_u} \right)^{\beta_u} \quad (44)$$

with  $\widehat{w}_u(r, \ell^Y)$  and  $\widehat{w}_s(r, \ell^Y)$  as given by (42) and (43), respectively. This fixes the wage rates and the price for health care as functions of the interest rate and the "skill-intensity" in final goods production,  $\ell^Y$ . Using  $L_s$  and  $L_u$  to denote the supply of skilled and unskilled labour, respectively, we can write

$$\ell^Y = \frac{L_s^Y}{L_u^Y} = \frac{L_s - L_s^H}{L_u - L_u^H} = \frac{L_s - \ell^H L_u^H}{L_u - L_u^H} = \frac{L_s - \left( \frac{\beta_s \alpha_u}{\beta_u \alpha_s} \right) \ell^Y L_u^H}{L_u - L_u^H}. \quad (45)$$

where we have employed  $\ell^H = \left( \frac{\beta_s \alpha_u}{\beta_u \alpha_s} \right) \ell^Y$  as from (39) and (41). The outer equation in (45) solves to

$$\ell^Y = \widehat{\ell}^Y (L_u^H) = \frac{L_s}{L_u - \left(1 - \frac{\beta_s \alpha_u}{\beta_u \alpha_s}\right) L_u^H}, \quad (46)$$

which fixes the skill-intensity as a function of unskilled labour demand in the health care sector (as well as the exogenous levels of skilled and unskilled labour supply).

Using the market clearing condition in the health care sector and inserting from (40) and (41), we obtain

$$\begin{aligned} H &= A^H L_u^H \left( \frac{\beta_K \widehat{w}_u (r, \widehat{\ell}^Y (L_u^H))}{\beta_u (r + \delta)} \right)^{\beta_K} \left( \frac{\beta_s \widehat{w}_u (r, \widehat{\ell}^Y (L_u^H))}{\beta_u \widehat{w}_s (r, \widehat{\ell}^Y (L_u^H))} \right)^{\beta_s} \\ &= A^H L_u^H \left( \frac{\beta_K \widehat{w}_u (r, \widehat{\ell}^Y (L_u^H))}{\beta_u (r + \delta)} \right)^{\beta_K} \left( \frac{\beta_s \alpha_u \widehat{\ell}^Y (L_u^H)}{\beta_u \alpha_s} \right)^{\beta_s}, \end{aligned}$$

with  $\widehat{w}_u (r, \widehat{\ell}^Y (L_u^H))$  and  $\widehat{\ell}^Y (L_u^H)$  as defined in (42) and (46), respectively. The equality can be solved to obtain the demand for unskilled labour as a function of the interest rate [and the equilibrium demand for health care  $H = \widehat{H} (\widehat{p} (r, \widehat{\ell}^Y (L_u^H)))$ ] such that ultimately,  $L_u^H = \widehat{L}_u^H (r)$ . This also fixes the skill-intensity  $\widehat{\ell}^Y (\widehat{L}_u^H (r))$  and, in turn, all prices as a

function of the interest rate. The remaining factor demand functions then follow as

$$\begin{aligned}
\widehat{L}_u^Y(r) &= L_u - \widehat{L}_u^H(r) \\
\widehat{L}_H^S(r) &= \left( \frac{\beta_s \alpha_u}{\beta_u \alpha_s} \right) \widehat{\ell}^Y \left( \widehat{L}_u^H(r) \right) \widehat{L}_u^H(r) = \frac{\left( \frac{\beta_s \alpha_u}{\beta_u \alpha_s} \right) L_s \widehat{L}_u^H(r)}{L_u - \left( 1 - \frac{\beta_s \alpha_u}{\beta_u \alpha_s} \right) \widehat{L}_u^H(r)} \\
\widehat{L}_Y^S(r) &= L_s - \widehat{L}_H^S(r) = \frac{L_s \left[ L_u - \widehat{L}_u^H(r) \right]}{L_u - \left( 1 - \frac{\beta_s \alpha_u}{\beta_u \alpha_s} \right) \widehat{L}_u^H(r)} \\
\widehat{K}^H(r) &= \frac{\beta_K \widehat{w}_u \left( r, \widehat{\ell}^Y \left( \widehat{L}_u^H(r) \right) \right)}{\beta_u} \widehat{L}_u^H(r) \\
&= \frac{\beta_K \alpha_u \left[ A^Y \left( \frac{\alpha_K}{r+\delta} \right)^{\alpha_K} \left( \frac{L_s}{L_u - \left( 1 - \frac{\beta_s \alpha_u}{\beta_u \alpha_s} \right) \widehat{L}_u^H(r)} \right)^{\alpha_s} \right]^{\frac{1}{1-\alpha_K}}}{\beta_u} \widehat{L}_u^H(r) \\
\widehat{K}^Y(r) &= \frac{\alpha_K \widehat{w}_u \left( r, \widehat{\ell}^Y \left( \widehat{L}_u^H(r) \right) \right)}{\alpha_u} \widehat{L}_u^Y(r) \\
&= \frac{\alpha_K \alpha_u \left[ A^Y \left( \frac{\alpha_K}{r+\delta} \right)^{\alpha_K} \left( \frac{L_s}{L_u - \left( 1 - \frac{\beta_s \alpha_u}{\beta_u \alpha_s} \right) \widehat{L}_u^H(r)} \right)^{\alpha_s} \right]^{\frac{1}{1-\alpha_K}}}{\alpha_u} \left[ L_u - \widehat{L}_u^H(r) \right].
\end{aligned}$$

Thus, in order to ensure non-negative factor inputs, we need to make but a single assumption, namely that  $L_u \geq \widehat{L}_u^H(r)$ .

This leaves  $r$  and  $\widehat{K}$  to be determined. The former follows from the capital market equilibrium

$$\widehat{K}^Y(r) + \widehat{K}^H(r) = K(r),$$

the latter follows from the goods market equilibrium

$$A^Y \left( \widehat{K}^Y(r) \right)^{\alpha_K} \left( \widehat{L}_s^Y(r) \right)^{\alpha_s} \left( \widehat{L}_u^Y(r) \right)^{\alpha_u} = C + \delta \left[ \widehat{K}^Y(r) + \widehat{K}^H(r) \right] + \dot{K}.$$

## 8.4 Solving the Numerical Problem

We pursue the following steps towards tracing out the numerical solution, sketched here for the benchmark scenario:

1. We derive from the first-order condition for consumption (25) the relationship

$$c_i(a, t_0 + a)^{-\sigma} = c_i(0, t_0)^{-\sigma} \exp \left\{ \int_0^a [\rho - r(t_0 + \hat{a}) + \mu_i(\hat{a}, t_0 + \hat{a})] d\hat{a} \right\}. \quad (47)$$

for  $i = s, u$ .

2. We derive the life-cycle budget constraint

$$\int_0^\omega \begin{bmatrix} w_i(t_0 + a)l(a) - c_i(a, t_0 + a) + \pi_i(a, t) \\ -\phi_i(a, t)p(t_0 + a)(h_i(a, t_0 + a) + e(S_i(a, t_0 + a))) \\ -\tau_i(a, t) + s(t_0 + a) \end{bmatrix} R(a, 0) da = 0,$$

with  $R(a, 0)$  as given by

$$R(\hat{a}, a) := \exp \left[ - \int_a^{\hat{a}} r(t + \hat{a} - a) d\hat{a} \right]. \quad (48)$$

We then insert (47) and obtain the consumption level

$$c_i(0, t_0) = \frac{\int_0^\omega \begin{bmatrix} w_i(t_0 + a)l(a) + \pi_i(a, t) - \tau_i(a, t) + s(t_0 + a) \\ -\phi_i(a, t)p(t_0 + a)(h_i(a, t_0 + a) + e(S_i(a, t_0 + a))) \end{bmatrix} R(a, 0) da}{\int_0^\omega \exp \left\{ \int_0^a \left[ \frac{1-\sigma}{\sigma} r(t_0 + \hat{a}) - \frac{\rho + \mu_i(\hat{a}, t_0 + \hat{a})}{\sigma} \right] d\hat{a} \right\} da} \quad (49)$$

for an individual born at  $t_0$ , contingent on the stream of health care,  $h_i(a, t_0 + a)$ , and the set of prices  $\{w_i(t_0 + a), r(t_0 + a), p(t_0 + a)\}$  over the interval  $[t_0, t_0 + \omega]$ . Finally, we need to keep track of the constraint on minimum consumption at the level of social security benefits. As is readily checked from the numerical analysis, this constraint is binding only at the highest ages.

3. We derive from the first-order condition for health care (27) a vector of age-specific demand levels

$$h_i(a, t_0 + a) = \left( \frac{\psi_i(a, t_0 + a)\eta_i(a, t_0 + a)M_i(t_0 + a)}{\phi_i(a, t_0 + a)p(t_0 + a)} \right)^{\frac{1}{1+M_i(t_0 + a)}} \quad (50)$$

for all  $a \in [0, \omega]$ .

4. We show in section 8.3 that the set of prices  $\{w_i(t_0 + a), p(t_0 + a)\}$  as well as all input and output quantities can be expressed in terms of the interest rate  $r(t_0 + a)$  alone.

5. Using (49) together with (50) we can calculate the life-cycle allocation for consumption,  $c_i(a, t_0 + a)$ , depending on the allocation for health expenditures,  $h_i(a, t_0 + a)$ ,  $\forall a \in [0, \omega]$  and on the set of prices  $\{w_i(t_0 + a), r(t_0 + a), p(t_0 + a)\}$  over the interval  $[t_0, t_0 + \omega]$ . Vice versa, the allocation of health expenditures can be calculated from the allocation of consumption and the macroeconomic prices.

6. We apply these calculations iteratively on initial guesses of  $c$  and  $h$ . We then use the results as an initial input to the age-structured optimal control algorithm, as pre-

sented in Veliov (2003). This yields an optimal allocation of individual consumption and health expenditures contingent on an initially assumed  $r(t_0 + a)$ .

7. Drawing on this, we apply the following recursive approximation algorithm: (i) Guess an initial interest rate  $r(t_0 + a)$  and derive the optimal life-cycle allocation. (ii) Based on this, calculate the market interest rate  $r^*(t_0 + a)$  from the capital market equilibrium  $\widehat{K}^Y(r(t_0 + a)) + \widehat{K}^H(r(t_0 + a)) = K(r(t_0 + a))$ . (iii) Adjust the initial interest rate, so that it approaches  $r^*(t_0 + a)$ , e.g. by setting  $r_1(t_0 + a) := r_0(t_0 + a) + \epsilon(r^*(t_0 + a) - r_0(t_0 + a))$ ,  $\epsilon \in (0, 1]$ . The process converges to an interest rate for which households optimise and capital demand equals capital supply. The output market clearing condition,  $Y(t_0 + a) = C(t_0 + a) + \dot{K}(t_0 + a) + \delta K(t_0 + a)$  then determines the dynamics of the capital stock to the next period. (iv) This process is reiterated in a recursive way, employing a solution algorithm based on Newton's method. Equations (49)-(50) allow us to verify ex-post an optimum life-cycle allocation for the focal cohort born at  $t_0$ . While the numerical algorithm cannot determine in a precise way the optimal allocation for other cohorts, it nevertheless structures the allocation in a way that approximates the optimum for all cohorts.

We solve the model over a period of 300 periods, covering the years 1850-2150. The number of periods is chosen to be this large in order for the initial and final conditions of the model simulation not to matter for the period of interest (1960-2015). The periods 1850 to 1950 are characterised by a steady state where all exogenous variables generating the model dynamics (i.e.  $A^Y$ ,  $A^H$ ,  $M_s$  etc.) over the period of interest are held constant. Beginning in 1950, we impose growth trends on the exogenous variables so as to generate the baseline model dynamics described in the main text. To generate the counterfactual experiments, we switch off the growth in the corresponding exogenous variables. The periods after 2015 describe a slow reduction in the growth rate of these exogenous variables over a period of 50 years and a steady-state over the remaining periods up to 2150. The simulation of the periods before and after the time frame of interest has no economic interpretation and only serves the purpose of providing a stable steady-state between the calibrated dynamic transition process.

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