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ROBOTS AND THE SKILL PREMIUM: AN AUTOMATION-BASED EXPLANATION OF WAGE INEQUALITY

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Abstract

We analyze the effects of automation on the wages of high-skilled and low-skilled workers and thereby on the evolution of wage inequality. Our model explains the simultaneous presence of i) increasing per capita GDP, ii) declining real wages of low-skilled workers, and iii) an increasing skill-premium. These developments are consistent with the experience in the United States over the past decades and have the potential to contribute to the explanation of the rise in overall income inequality that we have observed since the 1980s.

JEL classification: O11, O41, I24.

Keywords: Automation, declining real wages of low-skilled workers, income inequality, long-run economic growth, skill premium.

1 Introduction

Despite sustained economic growth in the United States over the past decades, the median real wage stagnated and the real wages of low-skilled workers even declined since the 1970s (Acemoglu and Autor, 2012; Autor, 2014; Mishel et al., 2015; Murray, 2016). At the same time, the wages of high-skilled workers with a bachelor's degree or higher have grown. Clearly, the overall development of the United States economy has therefore been characterized by a rise in the skill-premium and a higher dispersion of wages in general. This rise in wage-related inequality is surely one of the driving forces behind the rise in overall income inequality that we observed since the 1980s (Piketty and Saez, 2003; Atkinson et al., 2011; Piketty, 2014; Milanovic, 2016).[1]

A widely accepted and convincing explanation for the rise in the skill premium is skill-biased technological change that disproportionately raised the productivity of high-skilled workers over the past decades (cf. Acemoglu, 1998, 2002; Goldin and Katz, 2008). According to this explanation, the rise in the number of college-educated workers in the second half of the 20th century has led to a rise in the demand for technologies that are suited to their skills. The increase in the stock of these technologies – such as computers, programming languages, software for spreadsheet calculations and for the management of large databases – in turn has raised their productivity. Depending on the possibility to substitute high-skilled and low-skilled workers with each other in the production process, the rise in the stock of technologies that are biased towards high-skilled workers has the potential to raise their wages by more than the wages of low-skilled workers. If this is the case, endogenous skill-biased technological change widens the wage gap.

Other developments – notably international trade and outsourcing – have complemented skill-biased technological change in its effect on the wage differential (Autor et al., 2016). The intuition behind the effects of international trade and outsourcing on the dispersion of wages is straightforward. The production of goods that primarily require low-skilled labor input (simple toys, clothes, etc.) can easily be shifted to countries, in which labor is abundant and wages are substantially lower. Due to decreasing transport costs and globally decreasing tariffs in the 20th

[1] Other explanations include the reduction in wealth taxes and top marginal income tax rates since the 1980s, the emergence of superstar economics, where someone with either the skills or the luck to be slightly ahead of others in a certain domain such as sports, entertainment, or finance, is able to earn a disproportionate share of overall earnings in this domain, the reduction in the bargaining power of unions, and demographic changes such as declining birth rates and the associated concentration of inheritances or assortative mating, i.e., that nowadays spouses and life partners tend to have a similar level of education, which was not always the case.

century, these goods can ever more cheaply be exported back to the home market. As a result, firms with high demand for low-skilled labor tend to concentrate abroad, mainly in low-wage countries. By contrast, the production of goods that require a lot of skilled labor input (sophisticated machinery, airplane engines, etc.), cannot be shifted abroad to the same extent. Consequently, the firms producing them concentrate at home, where workers tend to be well-educated and wages are high. This implies, from the perspective of the home economy, that globalization leads a fall in the demand for low-skilled labor and a rise in the demand for high-skilled labor. As a result, the wages of high-skilled workers increase and the wages of low-skilled workers decrease according to standard economic arguments.

We show that there is another aspect that might have played an important role in explaining the rising skill premium and which has not been credited sufficiently up to know. Over the past decades, automation has made it possible to replace the production factor labor entirely – as far as different routine tasks in the production process are concerned. For example, industrial robots, which were unknown in the beginning of the 1950s, have become widely available and are applied at a large scale nowadays, particularly in the car industry (IFR, 2015). Tasks that previously had to be performed by workers are now undertaken by industrial robots in halls into which humans are not even allowed to enter. By the same token, 3D printing has allowed to reduce the amount of labor input in the production of customized products – such as hearing aids and prostheses – toward zero and it is now even used for the construction of entire buildings (Abeliansky et al., 2015; The Economist, 2017). Currently, self-driving cars and lorries are tested on various roads with the potential implication that millions of taxi and truck rivers could become obsolete in the not too distant future.

The crucial difference between automation and skill-biased technological change is that automation does not raise the productivity of labor (as does, for example, a standard computer that still has to be operated by a suitably skilled person), but that it renders the production factor labor entirely obsolete for given tasks (such as driving taxis in case of automated vehicles). While overall production per worker rises with automation, the marginal value product of labor might not, such that these two different measures of production start to diverge with automation. Furthermore, as compared to standard physical capital in the form of machines, assembly lines, and production halls, a rise in the stock of automation capital does not imply a higher demand for workers. If a firm invests in new machines and assembly lines, it needs the workers to operate them. By contrast, if a firm invests in a fleet of self-driving cars or in a production facility that operates with 3D printers instead of workers, this does not raise the demand for labor. Consequently, capital deepening, which was associated with rising wages in macroeconomics, could – in the future – lead to a replacement of labor and to lower wages instead of rising wages.

To analyze the distributive effects of automation, we incorporate automation capital as a new production factor into an otherwise standard and simple model of capital accumulation with low-skilled and high-skilled workers. Consistent with the stylized facts up to date, we assume that low-skilled labor is easier to automate than high-skilled labor.[2] The resulting framework is capable of generating automation-driven long-run growth even in the absence of technological progress and it explains the rise in the skill premium. In addition and in contrast to the model of skill-biased technological change, our framework is able to explain the reduction in the real wages of low-skilled workers that we have observed over the past decades in the United States.

As far as the related literature is concerned, the analysis of automation has received considerable attention most recently. To our knowledge, Steigum (2011) was the first to explicitly address the implications of the use of robots in a neoclassical type of growth model along the lines of Cass (1965) and Koopmans (1965). He shows that, in this setting, the possibility of sustained long-run growth emerges due to automation and that the labor share is set to fall with automation, which is consistent with the empirical evidence for the United States (Elsby et al., 2013; Karabarbounis and Neiman, 2014). However, he does not focus on wage inequality by heterogeneous types of workers. Prettner (2017) analyzes the effects of automation in a simpler framework based on Solow (1956). He shows that the results of Steigum (2011) carry over to this setting and quantifies the extent to which automation contributed to the reduction in the labor share of the United States between 1970 and 2010. Gasteiger and Prettner (2017) show that the implications of automation for long-run economic growth are different if the overlapping generations framework of Diamond (1965) is used instead of the Solow (1956) model or the framework of Cass (1965) as a baseline model to analyze automation. In the overlapping generations setting with automation, the economy always converges to stagnation, even if there is full replacement of labor by automation capital such that the production side of the economy resembles the properties of an AK growth model. The reason is that, in the overlapping generations framework, households exclusively save out of their first-period wage income, which is, however, reduced by automation due to the replacement of labor. This reduces the amount of overall investment in the economy,

[2] This holds at least up to know. However, progress in the development of machine learning algorithms has been very fast such that even non-routine, skill-intensive tasks become more and more automatable. Examples are diagnosing diseases and writing novels (Barrie, 2014).

which, in turn, reduces economic growth. The corresponding vicious circle implies a long-run stagnation of the economy and thereby explains the numerical findings of Sachs and Kotlikoff (2012), Sachs et al. (2015), and Benzell et al. (2015), according to which automation can reduce economic growth. While the numerical results in Sachs and Kotlikoff (2012) and Benzell et al. (2015) also show that the wages of high-skilled workers and low-skilled workers may diverge with automation, the other mentioned works do not analyze wage-related inequality.

As far as the endogenous growth literature is concerned, Acemoglu and Restrepo (2015), Hémous and Olsen (2016), and Prettner and Strulik (2017) have proposed frameworks that analyze the implications of automation within this strand of the literature. In Acemoglu and Restrepo (2015) and Hémous and Olsen (2016), R&D investments generate new varieties of tasks (in the former paper) and intermediate products (in the latter paper) that are initially non-automated. Firms can subsequently invest with the purpose to automate the corresponding production. Consequently, the wages of low-skilled workers rise with R&D-based innovations and fall with in-house innovation in automation. To the extent that R&D-based innovation is encouraged by automation, it could even be the case that the wages of low-skilled workers rise with automation in such a setting. By contrast, as far as wage inequality is concerned, the results of Prettner and Strulik (2017) are less benign because new innovations come in the form of the very machines by which the production of goods is automated. As such, automation reduces the wages of low-skilled workers to the extent that wage dispersion and inequality rise with economic growth as driven by innovation-driven automation.

Our contribution to the literature is i) that we set forth a simple framework of capital accumulation in the age of automation with a straightforward interpretation of automation capital that, in contrast to Sachs and Kotlikoff (2012) and Benzell et al. (2015), allows for the analytical analysis of wage inequality and ii) that our framework can explain the contemporaneous presence of rising per capita GDP, shrinking wages of high-skilled workers, and rising wage inequality as experienced by the United States economy over the past decades.

The paper is structured as follows. In Section 2, we present the central elements of our model and derive the laws of motion of physical capital per capita and of automation capital per capita. In Section 3, we solve for the long-run balanced growth rate and present our main results. We show that the model generates falling wages of low-skilled workers, a rising skill-premium, and positive per capita GDP growth with a rising automation level. In Section 4, we conclude and sketch out some scope for further research.

2 A simple model of automation and wage inequality

Consider an economy that is populated by households who invest a fraction s of their income. We abstract from endogenous investment decisions that would mainly complicate the exposition.[3] Time t evolves continuously and the population grows at rate n. There are four production factors: low-skilled workers denoted by L_u, high-skilled workers denoted by L_s, traditional physical capital in the form of machines, assembly lines, and production halls denoted by K, and automation capital in the form of industrial robots and 3D printers, denoted by P. According to its definition (Merriam-Webster, 2017), automation capital is a perfect substitute for low-skilled workers but it is still an imperfect substitute for high-skilled workers. Suppressing time arguments whenever this does not impair the clarity of exposition, the representative firm produces output Y according to the production function

$$Y = \left[(1-\beta)L_s^{\gamma} + \beta\left(P + L_u\right)^{\gamma}\right]^{\frac{1-\alpha}{\gamma}} K^{\alpha}, \tag{1}$$

where $\beta \in (0,1)$ is the production weight of low-skilled workers, $\gamma \in [0,1]$ measures the substitutability between both types of workers, where workers are perfect substitutes for $\gamma = 1$ and complements for $\gamma = 0$, and α is the elasticity of output with respect to traditional physical capital. Traditional physical capital and automation capital are the only savings/investment vehicles in the economy. Denoting the fraction of investment diverted to the accumulation of traditional capital by s_K and the rate of depreciation by δ, the laws of motion for both types of capital are given as in Prettner (2017):

$$\dot{K} = s_K s Y - \delta K, \tag{2}$$

$$\dot{P} = (1 - s_K) s Y - \delta P. \tag{3}$$

Assuming different rates of depreciation for both types of capital would not change the main qualitative results.

For simplicity, we abstract from endogenous education that would allow individuals to switch from being low-skilled to being high-skilled. For an R&D-based growth model with automation and skill-upgrading, but with a simpler production structure and only one type of capital, see Prettner and Strulik (2017). Considering education decisions in our framework would primarily affect the transitional

[3]See Steigum (2011) for an analysis of the growth effects of automation in a model with endogenous investments but without heterogeneous labor.

dynamics as has been shown by Prettner and Strulik (2017). Denoting the size of the workforce by $L = L_u + L_s$, defining the shares of high-skilled and low-skilled workers by $l_s = L_s/(L_s + L_u)$ and $l_u = L_u/(L_s + L_u)$, and referring to per capita counterparts of aggregate variables with lowercase letters, yields per capita GDP as

$$y = \left[(1-\beta)l_s^\gamma + \beta\left(p + l_u\right)^\gamma\right]^{\frac{1-\alpha}{\gamma}} k^\alpha. \tag{4}$$

This expression shows that the accumulation of traditional physical capital makes both types of labor more productive, while automation competes with low-skilled workers directly and with high-skilled workers indirectly depending on the extent to which high-skilled workers can be substituted by low-skilled workers. Essentially, automation changes the property of labor in the fundamental sense that labor becomes an accumulable production factor.

It is straightforward to show that the per capita dynamics of traditional capital and of automation capital are given by

$$\dot{k} = s_K \cdot s \cdot y - (\delta + n)k, \tag{5}$$

$$\dot{p} = (1 - s_K)s \cdot y - (\delta + n)p. \tag{6}$$

As a consequence, the per capita growth rates of traditional capital, g_k, and of automation capital, g_p, can be derived as

$$g_k = s_K s \left[(1-\beta)l_s^\gamma + \beta(p + l_u)^\gamma\right]^{\frac{1-\alpha}{\gamma}} k^{\alpha-1} - (\delta + n), \tag{7}$$

$$g_p = (1 - s_K)s \left[(1-\beta)l_s^\gamma + \beta(p + l_u)^\gamma\right]^{\frac{1-\alpha}{\gamma}} k^\alpha p^{-1} - (\delta + n). \tag{8}$$

These two equations fully describe the growth process of both both types of capital in our setting. The solution of the system allows us to keep track of the other variables in the model such as per capita GDP, wages of high-skilled workers, wages of low-skilled workers, and, by implication, the skill-premium.

3 Results

In Appendix A we show that a steady state exists in which the per capita stocks of both types of capital are positive but do not grow such that the economy stagnates as in Solow (1956). However, there is the more interesting case of a long-run balanced growth path along which the economy grows at a constant rate, despite the absence of technological progress. To calculate this growth rate, we use the definition of a balanced growth path according to which the per capita growth rates of both types of capital are constant, i.e., $\dot{g}_k = \dot{g}_p = 0$. Recalling Equations (7) and (8), this yields the result that the growth rates of k and p have to be equal along the balanced growth path such that $\dot{k}/k = \dot{p}/p$. For $\lim_{p\to\infty}$ and constant l_s and l_u, we can equate (7) and (8) and use the approximation $(1-\beta)l_s^\gamma + \beta(p+l_u)^\gamma \approx \beta(p+l_u)^\gamma \approx \beta p^\gamma$ to derive the common asymptotic growth rate of traditional physical capital and automation capital as

$$g = \beta^{\frac{1-\alpha}{\gamma}} \cdot s \cdot s_K^\alpha (1-s_K)^{1-\alpha} - (\delta + n). \tag{9}$$

Equation (4) implies that per capita output also grows at rate g because

$$\begin{aligned} ln(y) &= \frac{1}{\gamma}(1-\alpha)\cdot ln\left[(1-\beta)l_s^\gamma + \beta\left(p+l_u\right)^\gamma\right] + \alpha \cdot ln(k) \\ &\approx \frac{1}{\gamma}(1-\alpha)\cdot ln\left(\beta p^\gamma\right) + \alpha\cdot ln(k) \\ \Rightarrow \frac{\mathrm{d}ln(y)}{\mathrm{d}t} &= g_y = (1-\alpha)g_p + \alpha g_k = g. \end{aligned}$$

At this stage we can state our first central result.

Proposition 1. *In our framework, there exists a balanced growth path with positive long-run economic growth at rate g as given by Equation (9). This growth rate increases with the savings rate (s) and with the substitutability between low-skilled and high-skilled workers (γ), whereas it decreases with the rates of population growth (n) and depreciation (δ).*

Proof. The proposition follows immediately from inspecting Equation (9) and noting that $\beta < 1$ such that an increase in γ raises the first term in this expression. □

The results in Proposition 1 generalize the results of Prettner (2017) to a model with two different types of workers that have different levels of skills, where low-skilled labor is easier to substitute by automation than high-skilled labor. The intuition for the finding of perpetual growth in the absence of technological progress is that automation turns labor into an accumulable production factor. The main results carry over from Prettner (2017) in the sense that i) a rise in the savings rate raises economic growth because it implies that both types of capital accumulate at a faster rate, ii) a rise in the population growth rate leads to faster dilution of both types of capital and therefore reduces economic growth, and iii) faster depreciation reduces the accumulation of both types of capital and therefore reduces economic growth. However, there is also the new result that the substitutability between low-skilled and high-skilled workers plays a crucial role. The easier it is to substitute between the two types of workers, the easier it is for automation capital to raise the amount of effective labor in the economy, i.e., the easier it is to turn labor into an accumulable production factor by relying on automation. Consequently, the better low-skilled workers and high-skilled workers can be substituted, the stronger is the growth effect of automation.

At that stage, we can state our second central result.

Proposition 2. *In our framework, the accumulation of automation capital leads to*

i) decreasing wages of low-skilled workers,

ii) decreasing wages of high-skilled workers if low-skilled workers and high-skilled workers are easy to substitute,

iii) an increasing skill premium.

Proof. Assuming perfect competition, the wages of high-skilled workers (w_s) and the wages of low-skilled workers (w_u) are given by

$$w_s = (1-\alpha)\frac{Y}{L_s^{1-\gamma}}\frac{1-\beta}{(1-\beta)L_s^{\gamma}+\beta\,(P+L_u)^{\gamma}}, \tag{10}$$

$$w_u = (1-\alpha)\frac{Y}{(P+L_u)^{1-\gamma}}\frac{\beta}{(1-\beta)L_s^{\gamma}+\beta\,(P+L_u)^{\gamma}}. \tag{11}$$

The effect of an increase in the stock of automation capital on the wages of low-skilled workers is:

$$\frac{\partial w_u}{\partial P} = \frac{(1-\alpha)\beta Y}{(P+L_u)^{2-\gamma}}\frac{\{(1-\alpha-\gamma)\beta\,(P+L_u)^{\gamma}-(1-\gamma)\left[(1-\beta)L_s^{\gamma}+\beta\,(P+L_u)^{\gamma}\right]\}}{\left[(1-\beta)L_s^{\gamma}+\beta\,(P+L_u)^{\gamma}\right]^2}. \tag{12}$$

Since $(1-\alpha-\gamma)\beta\,(P+L_u)^{\gamma} < (1-\gamma)\beta\,(P+L_u)^{\gamma}$, the numerator of the second term is always negative and so is the whole derivative. Consequently, the accumulation of automation capital reduces the wages of low-skilled workers. This proves part i) of the proposition.

The effect of an increase in the stock of automation capital on the wages of high-skilled workers is:

$$\frac{\partial w_s}{\partial P} =$$

$$= (1-\alpha)Y\frac{(1-\beta)\beta L_s^{\gamma}}{L_s(P+L_u)^{1-\gamma}}\frac{1-\alpha-\gamma}{\left[(1-\beta)L_s^{\gamma}+\beta\,(P+L_u)^{\gamma}\right]^2} = \begin{cases} \geq 0 & \text{for} \quad 1-\alpha \geq \gamma, \\ < 0 & \text{for} \quad 1-\alpha < \gamma. \end{cases} \tag{13}$$

The influence of automation on the wages of high-skilled workers is therefore ambiguous and depends on the substitutability between both types of labor. If γ is high and substitution is easy, an increase in the use of robots even reduces the wages of high-skilled workers. This proves part ii) of the proposition.

The skill-premium is defined as the ratio of the wages of high-skilled workers to the wages of low-skilled workers:

$$\frac{w_s}{w_u} = \frac{1-\beta}{\beta}\left(\frac{P+L_u}{L_s}\right)^{1-\gamma}. \tag{14}$$

As long as $\gamma < 1$, which implies the empirically relevant case of imperfect substitution between the two types of skills as required in the proposition, an increase in the stock of automation capital P raises the skill premium. This proves part iii) of the proposition. □

The intuition for i) is simply that competition by automation capital reduces the wages of workers whose skills have been made obsolete. However, and this is shown in part ii) of the proposition, also the wages of high-skilled workers are negatively affected by automation if low-skilled workers can substitute for high-skilled workers to a certain degree. Since the wages of high-skilled workers either increase with the extent of automation – or at least decrease by less than the wages of high-skilled workers – this implies a rising skill-premium, i.e., it implies part iii) of Proposition 2. Altogether, our results show that automation leads to rising per capita GDP, a reduction in the wages of low-skilled workers, and an ambiguous change in the wages of high-skilled workers. This development is in line with the data for the United States since the 1970s as presented in Acemoglu and Autor (2012) and Autor (2014). Consequently, automation is likely to be an important element in the overall explanation of the evolution of wage inequality.

Table 1: Parameter values for the numerical solution

Parameter	Value	Parameter	Value
s	0.25	s_K	0.55
α	0.33	β	0.60
γ	0.50	δ_K	0.05
δ_P	0.50	n	0.009
l_s	0.25	l_u	0.75
$p(0)$	164/10000	$k(0)$	1

To illustrate our results, we solve the model numerically for the parameter values displayed in Table 1. Since there are many different mechanisms that determine long-run economic growth and wage inequality (which our simplified model that is focused on automation does not capture), it would be a highly misleading exercise to calibrate the model to real-world data. Instead, the numerical results should be thought of illustrations of the transitional dynamics of the theoretical framework and of the result that there can be positive long-run economic growth in this setting.

The results for long-run growth in k and p are shown by means of a phase portrait for different initial conditions in Figure 1. It is clear that, for the parameter values as given in Table 1, there exists a balanced growth path with positive long-run economic growth to which the economy converges for given initial conditions. The implied skill premium of the model is shown in Figure 2. We observe an increase in the skill premium along the balanced growth path that levels off over time.

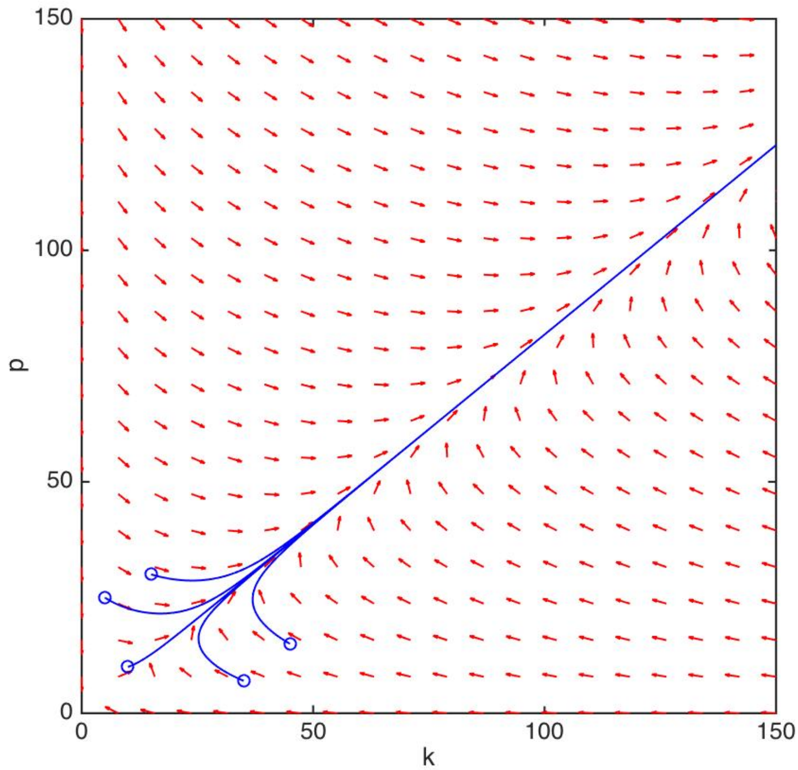

Figure 1: Phase diagram for the evolution of traditional physical capital per capita (k) and automation capital per capita (k) for different initial conditions.

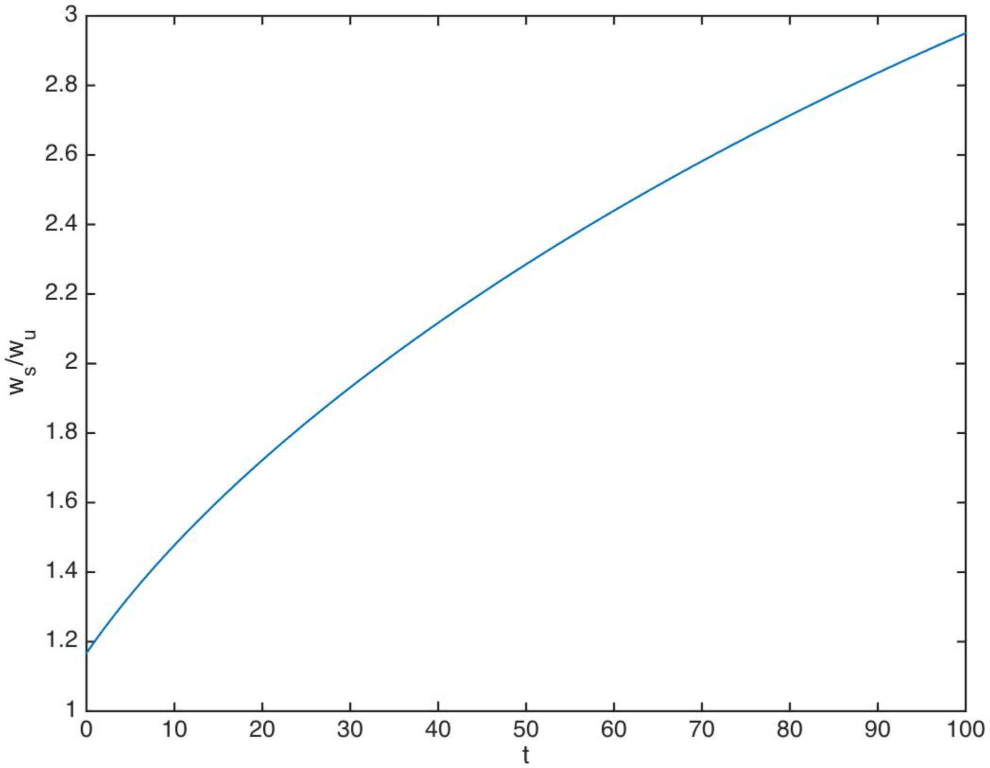

Figure 2: The implied evolution of the skill premium (w_s/w_u) of the model.

4 Conclusions

We analyze the effects of automation in a model with low-skilled and high-skilled workers in which low-skilled workers are easier to automate than high-skilled workers. We show that i) there is the possibility for perpetual economic growth despite the absence of technological progress, ii) automation decreases the real wages of low-skilled workers and has the potential to even decrease the wages of high-skilled workers, iii) automation raises the skill premium. All three results are consistent with the experience of the United States over the past decades and help to explain why the less well-educated did not benefit, despite overall economic growth. As such, automation is likely to be an important aspect in the explanation over the evolution of overall income inequality that has so far not received appropriate attention.

For future research it would be interesting to include skill-biased technological change, globalization, and automation within a single framework to quantify the relative importance of the different mechanisms that affect the skill-premium. Clearly, such a large-scale simulation study is beyond the scope of the present paper.

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Appendix

A The stagnation steady state

To find the interior steady state in which long-run growth is zero as in Solow (1956), we set (5) and (6) equal to zero. For obvious reasons, $\delta + n > 0$ has to be fulfilled for $\dot{k} = 0$. We assume that this is the case for the following analysis. From (5), we get the ($\dot{k} = 0$)-isocline in the (k, p)-space as

$$k_1 := \left(\frac{s_m s}{\delta + n}\right)^{\frac{1}{1-\alpha}} \left[(1-\beta) l_s^\gamma + \beta (p + l_u)^\gamma\right]^{\frac{1}{\gamma}} . \tag{A.1}$$

From (6), we get the $(\dot{p}=0)$-isocline as

$$k_2 := \left[\frac{\delta+n}{(1-s_m)s}\right]^{\frac{1}{\alpha}} \left\{\frac{p}{[(1-\beta)l_s^\gamma + \beta(p+l_u)^\gamma]^{\frac{1-\alpha}{\gamma}}}\right\}^{\frac{1}{\alpha}} \tag{A.2}$$

The steady state can then be derived by equalizing the two expressions

$$\frac{1-\beta}{\beta} l_s^\gamma + (p+l_u)^\gamma \stackrel{!}{=} \Bigg[\underbrace{\frac{(\delta+n)^{\frac{1}{1-\alpha}}}{\beta^{\frac{1}{\gamma}}(1-s_m)s(s_m s)^{\frac{\alpha}{1-\alpha}}}}_{=:c}\Bigg]^\gamma p^\gamma, \tag{A.3}$$

$$\iff \frac{1-\beta}{\beta} l_s^\gamma + (p+l_u)^\gamma - c^\gamma p^\gamma \stackrel{!}{=} 0, \tag{A.4}$$

where we define the term in square brackets in the first line by c. For $c \leq 1$ this equation cannot be fulfilled. To see this, we define the function $f(p) := p^\gamma$ that is strictly monotonically increasing. Consequently, we have $(p+l_u)^\gamma > p^\gamma$ and therefore

$$\frac{1-\beta}{\beta} l_s^\gamma + (p+l_u)^\gamma - c^\gamma p^\gamma > \frac{1-\beta}{\beta} l_s^\gamma > 0. \tag{A.5}$$

This means that there is no intersection between the two isoclines for $l_s > 0$ and $\beta \neq 1$.

For the case $c > 1$, we define the function $F(p) := (1-\beta)l_s^\gamma/\beta + (p+l_u)^\gamma - c^\gamma p^\gamma$, which is strictly monotonically decreasing. Consequently, F has at most one root such that at most one steady state exists. Furthermore, $F(0) > 0$ and we can show by means of L'Hospital that $\lim_{p\to\infty} F(p) < 0$. The intermediate value theorem therefore implies that there has to be a root for the case of $c > 1$. Consequently, there is a unique steady state with $k, p > 0$. For this steady state, we have that per capita variables are constant and aggregate variables grow at the rate of population growth, n.

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