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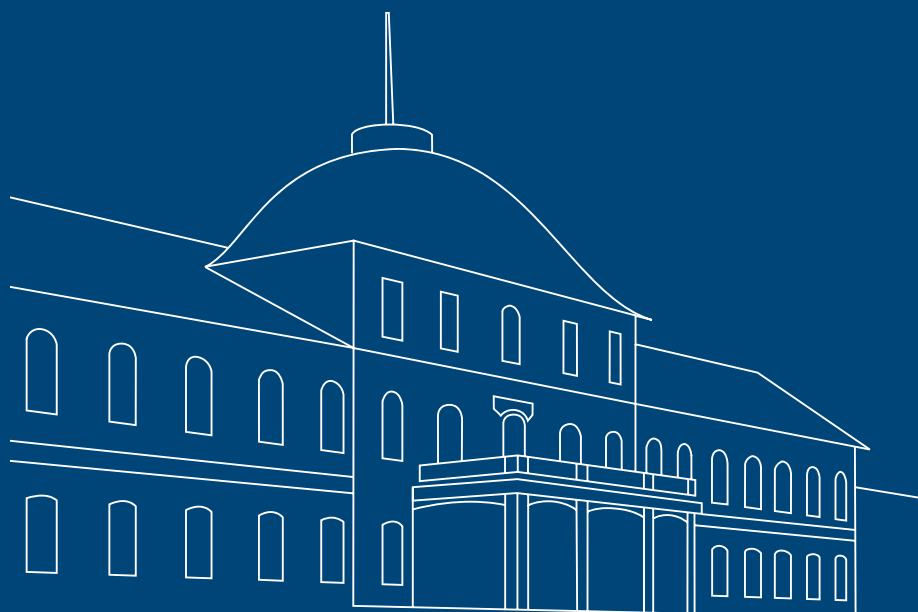
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DISCUSSION PAPER 18-2016

## THE IMPLICATIONS OF AUTOMATION FOR ECONOMIC GROWTH AND THE LABOR SHARE

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# The implications of automation for economic growth and the labor share

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## Abstract

We introduce automation into a standard model of capital accumulation and show that (i) there is the possibility of perpetual growth, even in the absence of technological progress; (ii) the long-run economic growth rate declines with population growth, which is consistent with the available empirical evidence; (iii) there is a unique share of savings diverted to automation that maximizes long-run growth; (iv) the labor share declines with automation to an extent that fits to the observed pattern over the last decades.

**JEL classification:** O11, O33, O41.

**Keywords:** automation, robots, machine learning, perpetual economic growth, declining labor share, inequality.

# 1 Introduction

Automation has already taken over many (and will take over even more) of the tasks for which at least a small amount of labor input had been necessary in the past. For example, in the car industry, robots perform many production steps in an autonomous way; 3D printers are producing customized products with a minimal labor input; devices based on machine learning are already able to diagnose some diseases, to translate texts between different languages, and to write simple newsflashes and reports; moreover, driverless cars and lorries are soon expected to transport passengers and goods from location A to location B without having to rely on the driving skills of humans (cf. *The Economist*, 2014; Abeliansky et al., 2015; Lanchester, 2015; Brynjolfsson and McAfee, 2016).

To get a glimpse on the macroeconomic consequences of these developments, we introduce automation into the standard framework of Solow (1956). We show that (i) similar to Steigum (2011), perpetual growth is possible in such a framework even in the absence of technological progress; (ii) the long-run economic growth rate declines with population growth, which is consistent with the available empirical evidence; (iii) there is a unique share of savings diverted to automation that maximizes the long-run growth rate of the economy; and (iv) the labor share declines with automation. According to our calculations, the introduction of automation as it has been observed in the data between the 1970s and the 2010s implies a reduction of the aggregate labor income share by around 5.5 percentage points, which is roughly in line with the observations reported by Karabarounis and Neiman (2014). Considering the fact that capital income is typically much more unevenly distributed than labor income, this could have led to an increase in inequality as observed in most developed countries over the last decades.

The main policy conclusion that emanates from our analysis is that it might be very useful to design a compensation scheme for the losers of automation technologies. Doing so could help to distribute the potentially enormous gains of automation more evenly among various parts of the society and thereby to reduce the resistance to automation. Such a strategy could allow to adopt automation technologies, while, at the same time, to keep inequality in check.

# 2 The model

Consider an economy with three production factors, labor, traditional capital (machines, assembly lines, etc), and automation capital (robots, 3D printers, etc). Time  $t$  evolves continuously and the workforce grows at rate  $n$ . Traditional capital and automation capital can be accumulated and they depreciate at rate  $\delta$ . Labor and machines are imperfect substitutes, while automation capital is – by its definition – a

perfect substitute for labor.

There is a continuum of firms with each of them having access to a Cobb-Douglas production function of the form

$$Y(t) = A(t)[L(t) + P(t)]^{1-\alpha}K(t)^\alpha, \quad (1)$$

where  $Y(t)$  is aggregate output,  $L(t)$  refers to labor,  $K(t)$  denotes the stock of traditional capital,  $P(t)$  denotes the stock of automation capital,  $\alpha$  is the elasticity of final output with respect to traditional capital, and  $A(t) \equiv 1$  refers to the level of technology, which we deliberately normalize to 1. The reason for this normalization is that one of our central result, the potential for perpetual long-run economic growth due to automation, is best illustrated by abstracting from a second source of long-run growth such as technological progress. Peretto and Saeter (2013) analyze the effects of endogenous investments into R&D that increases the elasticity of output with respect to capital,  $\alpha$ . In the long-run limit of their model,  $\alpha$  tends to 1 such the production structure resembles those of an  $AK$ -type of growth model in which perpetual growth based on physical capital accumulation becomes feasible. Furthermore, during the transition toward the long-run limit, the labor share decreases in their framework.

Due to perfect competition, the factor rewards implied by Equation (1) are given by

$$w(t) = (1 - \alpha) \left[ \frac{K(t)}{L(t) + P(t)} \right]^\alpha \quad r(t) = R(t) - \delta = \alpha \left[ \frac{L(t) + P(t)}{K(t)} \right]^{1-\alpha} - \delta, \quad (2)$$

where  $w(t)$  is the wage rate,  $r(t)$  is the interest rate, and the owners of robots are compensated by  $w(t) - \delta$ .

The economy is closed and we abstract from a government such that output is used for consumption  $C(t)$  and savings  $S(t)$  according to  $Y(t) = C(t) + S(t)$ . In such a setting, savings are equal to investment  $I(t)$  to the extent that  $I(t) = S(t) = sY(t)$ , where  $s$  is the exogenous constant savings rate. In contrast to the standard Solow (1956) model, investments can be made in terms of two different forms of capital: traditional capital and automation capital. For simplicity, we assume that a share  $s_m$  of savings is diverted to investment in traditional capital and a share  $1 - s_m$  is diverted to investment in automation. Altogether, this setup yields the following accumulation equations:

$$\dot{K}(t) = s_m I(t) - \delta K(t), \quad \dot{P}(t) = (1 - s_m) I(t) - \delta P(t). \quad (3)$$

Using the production function (1), the growth rates of both types of capital can be

written as

$$\frac{\dot{K}(t)}{K(t)} = s_m s \left[ \frac{K(t)}{L(t) + P(t)} \right]^{-(1-\alpha)} - \delta, \quad (4)$$

$$\frac{\dot{P}(t)}{P(t)} = (1 - s_m) s \frac{1 + [P(t)/L(t)]}{P(t)/L(t)} \left[ \frac{K(t)}{L(t) + P(t)} \right]^\alpha - \delta. \quad (5)$$

Output per worker is given by

$$y(t) = \frac{Y(t)}{L(t)} = [1 + p(t)]^{1-\alpha} k(t)^\alpha, \quad (6)$$

where lowercase letters refer to variables in terms of per worker units, i.e., for any variable  $X(t)$  we have that  $x(t) = X(t)/L(t)$ . In the Appendix we show that the following dynamic system fully describes the evolution of the economy

$$\begin{aligned} \dot{k}(t) &= s_m s [1 + p(t)]^{1-\alpha} k(t)^\alpha - \delta \frac{K(t)}{L(t)} - nk(t), \\ \dot{p}(t) &= (1 - s_m) s [1 + p(t)]^{1-\alpha} k(t)^\alpha - \delta \frac{P(t)}{L(t)} - np(t), \end{aligned}$$

and that the economy converges to a path along which traditional capital per worker, automation capital per worker, and GDP per worker all grow at the common constant rate

$$g = s \cdot s_m^\alpha (1 - s_m)^{1-\alpha} - \delta - n. \quad (7)$$

If the first term on the right hand side is large (e.g., because of a large enough savings rate), this growth rate is positive. The solution for which Equation (7) is zero or negative resembles the standard properties of the steady state in the Solow (1956) model, where the long-run economic growth rate is zero. From now on we focus on the solution for which Equation (7) is positive. Altogether, this affords the following proposition.

**Proposition 1.** *If automation is considered as a perfect substitute for labor in the Solow (1956) model, then*

- (i) *there is the potential for perpetual economic growth driven solely by capital accumulation;*
- (ii) *if there is perpetual long-run growth, the long-run growth rate decreases with the rate of population growth;*
- (iii) *if there is perpetual long-run growth, the growth rate of the economy increases with the share of savings that is used for automation (traditional capital) as long*

as the fraction of savings diverted to traditional capital is larger (smaller) than the elasticity of output with respect to traditional capital.

*Proof.* Parts (i) and (ii) follow immediately by inspection of Equation (7). For the proof of part (iii) we calculate the derivative of  $g$  with respect to  $s_m$ :

$$\frac{\partial g}{\partial s_m} = s \cdot s_m^{\alpha-1} (1 - s_m)^{-\alpha} (\alpha - s_m).$$

We see that this expression is positive if  $\alpha - s_m$  is positive and it is negative if  $\alpha - s_m$  is negative.  $\square$

Part (i) of the proposition contrasts with the standard neoclassical growth model without technological progress in which the rate of long-run growth is zero. The reason for perpetual growth in our case is that automation is a perfect substitute for labor, which helps to overcome the diminishing marginal product of traditional capital installed in the form of machines and assembly lines. This result is also present in the interesting work of Steigum (2011) on robot technology in an optimal growth model and it is consistent with the empirical result of Graetz and Michaels (2015) who find that the intensification of the use of industrial robots boosts growth of productivity.

Part (ii) of the proposition is explained by the fact that, since the diminishing marginal product of physical capital in the standard model is overcome by the use of automation, variables that reduce the overall accumulation rate of physical capital – such as capital dilution due to population growth – also reduce the long-run economic growth rate. In contrast to the positive effect of population growth on long-run economic growth as found in the semi-endogenous growth theory (see, for example, Jones, 1995), our result is consistent with the available empirical evidence for developed countries throughout the 20th Century (cf. Brander and Dowrick, 1994; Kelley and Schmidt, 1995; Ahituv, 2001; Li and Zhang, 2007; Herzer et al., 2012).

The intuition for part (iii) of the proposition is the following. A reduction in the share of gross investment diverted to traditional capital would lead, *ceteris paribus*, to a *reduction* in economic growth. However, the reduction in the share of gross investments diverted to traditional capital comes with a corresponding increase in the share of gross investments diverted to automation. The latter would, *ceteris paribus*, lead to an *increase* in economic growth. If the fraction of gross investments diverted to machines is larger (smaller) than the elasticity of final output with respect to traditional capital, the reduction in growth due to a lower accumulation rate of machines is smaller (larger) than the corresponding increase in the rate of economic growth due to an increase in the accumulation rate of automation. Consequently, economic growth is maximized if  $s_m = \alpha$ .

Next, we turn our attention to the implication that the introduction and initial adoption of automation has on the labor income share of an economy. In our case,

aggregate labor income is given by

$$w(t)L(t) = (1 - \alpha) \left[ \frac{K(t)}{L(t) + P(t)} \right]^\alpha L(t), \quad (8)$$

which implies that the labor income share pins down to

$$\frac{w(t)L(t)}{Y(t)} = (1 - \alpha) \frac{L(t)}{L(t) + P(t)}. \quad (9)$$

We immediately see that the accumulation of automation capital reduces the labor income share in such a setting and summarize this finding in the following proposition.

**Proposition 2.** *If we consider automation in a standard Solow (1956) model, an increase in the stock of automation capital reduces the labor income share of the economy.*

The intuition for this finding is the following. From the production technology it is obvious that the wage rate decreases and the capital rental rate increases, if, ceteris paribus, the stock of automation capital increases. Since the income that is generated by automation is used to compensate capital owners, this implies that the capital income share increases and the labor income share declines. To put it differently, automation competes with labor and therefore its widespread adoption reduces wages, while, at the same time, the income that automation generates is channeled to the capital owners. Consequently, our framework proposes a complementary way of explaining the empirical finding of a decreasing labor income share in most developed countries over the last decades (see, for example, Karabarbounis and Neiman, 2014, for a discussion and for complementary channels).

### 3 Numerical assessment

In this section we illustrate the trajectories that are implied by our model for parameter values that are either taken from the literature or that are implied by the data for the United States (cf. World Bank, 2015). We set the gross savings rate  $s$  equal to the average gross domestic investment rate over the years 2000 to 2013 and the population growth rate  $n$  equal to the geometric average of the population growth rate over the years 2000 to 2013. Furthermore, we use a value of 0.3 for the elasticity of final output with respect to physical capital ( $\alpha$ ), which is in line with the literature (cf. Jones, 1995; Acemoglu, 2009; Grossmann et al., 2013). Finally, we set the rate of depreciation equal to  $\delta = 0.04$  as in Grossmann et al. (2013) and we use a value of 0.7 for  $s_m$  such that the effects of automation become visible in the graphs.

In Figure 1 we plot, on the left side, the traditional capital stock per capita, the automation capital stock per capita, and per capita GDP against time from  $t = 0$  to  $t = 100$ . On the right side we plot the corresponding growth rates. The solid lines refer



to the baseline parameter specification. We clearly observe exponential growth in the traditional capital stock, the stock of automation capital, and per capita GDP with no tendency to level off in the long run. Furthermore, we see that the growth rates of these variables converge toward their long-run solutions that are clearly positive. We also show the impact of an increase in the population growth rate of  $n = 0.009$  to a rate of  $n = 0.02$ , which is displayed by the dashed lines. We observe that the country with the higher population growth rate attains a lower growth rate of per capita GDP, even in the long run.

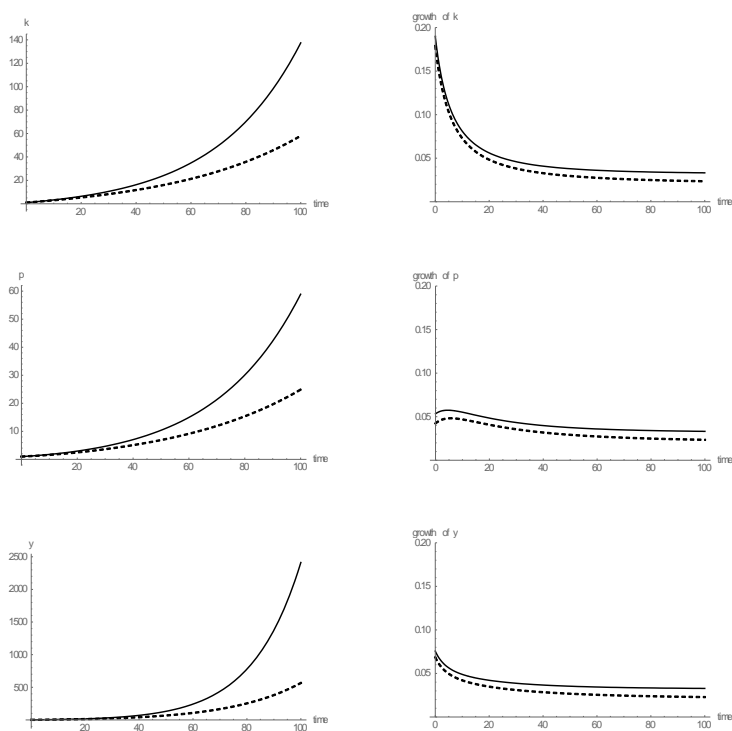


Figure 1: Levels of  $k$ ,  $p$ ,  $L$ , and  $y$  (left side) and growth rates of  $k$ ,  $p$ ,  $L$ , and  $y$  (right side). The solid lines represent the original solution, while the dashed lines represent the solution with the higher savings rate.

Finally, we assess the implied impact of the introduction of automation on the labor share. Karabarounis and Neiman (2014) document a reduction of the global labor share by around 5 percentage points from the early 1970s to the 2010s. Given that the fraction of industrial robots to the total capital stock in advanced economies has been estimated as 2.25 percent in 2007 according to Graetz and Michaels (2015), and assuming that it was close to zero in the beginning of the 1970s, our framework implies a decline of the labor share by around 5.5 percentage points, which is roughly in line with the data.

## 4 Conclusions

We introduced automation into the original model of Solow (1956). While the stock of automation capital is accumulated in a similar vein as traditional capital, its properties in the production process resemble those of labor. We show that, in such a setting, there is perpetual growth of per capita output, even in the absence of technological progress. Furthermore, the long-run economic growth rate decreases with population growth, which is consistent with the available empirical evidence for developed countries in the 20th Century. Finally, we show that there is a unique share of savings diverted to the accumulation of automation capital that maximizes the long-run growth rate.

Our framework has the potential to explain the decrease in the labor income share that has been observed in developed countries over the past decades. The reason is that automation competes closely with the production factor labor, while, at the same time, the income that automation generates is channeled toward the capital owners. Quantitatively, our framework implies a decline of the labor share by around 5.5 percentage points, which is roughly in line with the decline reported by Karabarbounis and Neiman (2014).

The main policy conclusion from our analysis derives from the fact that automation has the potential to raise overall living standards substantially, while, at the same time, workers could be adversely affected. As a consequence, inequality would increase. To reduce the anticipated opposition to automation from labor unions and to mitigate the increase in inequality, it might be desirable to set up a compensation scheme that is used to support the losers of automation technologies. That said, especially in economies that are aging rapidly, automation is a potential solution to overcome at least those problems that are caused by the aging-induced scarcity of labor.

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# Appendix

## A Derivations

### A.1 Derivation of Equation (5)

Using Equation (3), together with the production function (1), we get

$$\frac{\dot{P}(t)}{P(t)} = (1 - s_m)s[L(t) + P(t)]^{1-\alpha}K(t)^\alpha P(t)^{-1} - \delta.$$

Multiplying the first term on the right hand side by  $\{[L(t) + P(t)]/[L(t) + P(t)]\}^\alpha$  yields

$$\frac{\dot{P}(t)}{P(t)} = (1 - s_m)s \left[ \frac{1 + P(t)/L(t)}{P(t)/L(t)} \right] \left[ \frac{K(t)}{L(t) + P(t)} \right]^\alpha - \delta.$$

### A.2 Derivation of the long-run accumulation rate of machines and automation

Reformulating the machine accumulation equation in per-capita terms yields

$$\frac{\dot{K}(t)}{L(t)} = s_m s [1 + p(t)]^{1-\alpha} k(t)^\alpha - \delta \frac{K(t)}{L(t)}.$$

Reformulating the automation accumulation equation in per-capita terms yields

$$\frac{\dot{P}(t)}{L(t)} = (1 - s_m)s [1 + p(t)]^{1-\alpha} k(t)^\alpha - \delta \frac{P(t)}{L(t)}.$$

The dynamics of  $k(t)$  and  $p(t)$  are then given by

$$\begin{aligned} \dot{k}(t) &= \frac{d\frac{K(t)}{L(t)}}{dt} = \frac{\dot{K}(t)}{L(t)} - \frac{K(t)}{L(t)^2} \dot{L}(t) = \frac{\dot{K}(t)}{L(t)} - k(t) \frac{\dot{L}(t)}{L(t)} = \frac{\dot{K}(t)}{L(t)} - nk(t), \\ \dot{p}(t) &= \frac{d\frac{P(t)}{L(t)}}{dt} = \frac{\dot{P}(t)}{L(t)} - \frac{P(t)}{L(t)^2} \dot{L}(t) = \frac{\dot{P}(t)}{L(t)} - p(t) \frac{\dot{L}(t)}{L(t)} = \frac{\dot{P}(t)}{L(t)} - np(t). \end{aligned}$$

Taken together, these results imply the following system of equations for the evolution of machines per worker and automation capital per worker

$$\begin{aligned} \dot{k}(t) &= s_m s [1 + p(t)]^{1-\alpha} k(t)^\alpha - \delta \frac{K(t)}{L(t)} - nk(t), \\ \dot{p}(t) &= (1 - s_m)s [1 + p(t)]^{1-\alpha} k(t)^\alpha - \delta \frac{P(t)}{L(t)} - np(t), \end{aligned}$$

In terms of growth rates we have

$$\begin{aligned}\frac{\dot{k}(t)}{k(t)} &= s_m s \left[ \frac{1+p(t)}{k(t)} \right]^{1-\alpha} - \delta - n, \\ \frac{\dot{p}(t)}{p(t)} &= (1-s_m)s \left[ \frac{1+p(t)}{p(t)} \right]^{1-\alpha} \left[ \frac{k(t)}{p(t)} \right]^\alpha - \delta - n.\end{aligned}$$

Now we denote the growth rate of a variable  $x$  by  $g_x$  and the growth rate of its growth rate by  $g_{g_x}$ . Then we have

$$g_k = s_m s \left[ \frac{1+p(t)}{k(t)} \right]^{1-\alpha} - \delta - n, \quad (10)$$

$$g_p = (1-s_m)s \left[ \frac{1+p(t)}{p(t)} \right]^{1-\alpha} \left[ \frac{k(t)}{p(t)} \right]^\alpha - \delta - n, \quad (11)$$

$$\begin{aligned}\Rightarrow \log(g_k + \delta + n) &= \log(s_m) + \log(s) + (1-\alpha) \log[1+p(t)] \\ &\quad - (1-\alpha) \log[k(t)]\end{aligned} \quad (12)$$

$$\begin{aligned}\Rightarrow \log(g_p + \delta + n) &= \log(1-s_m) + \log(s) + (1-\alpha) \log[1+p(t)] \\ &\quad - (1-\alpha) \log[p(t)] + \alpha \log[k(t)] - \alpha \log[p(t)],\end{aligned} \quad (13)$$

$$\Rightarrow g_{(g_k+\delta+n)} = (1-\alpha) \frac{\dot{p}(t)}{1+p(t)} - (1-\alpha)g_k, \quad (14)$$

$$\Rightarrow g_{(g_p+\delta+n)} = (1-\alpha) \frac{\dot{p}(t)}{1+p(t)} - (1-\alpha)g_p + \alpha g_k - \alpha g_p. \quad (15)$$

Since, at the long-run equilibrium [for large  $p(t)$ ], we have that

$$\frac{\dot{p}(t)}{1+p(t)} \approx g_p,$$

Equations (14) and (15) imply that the economy converges to a long-run growth rate with  $g_p \approx g_k \equiv g$ . Note that, for large  $p(t)$  and large  $k(t)$ , we have

$$\left[ \frac{1+p(t)}{p(t)} \right]^{1-\alpha} \approx 1, \quad \frac{p(t)}{k(t)} \approx \frac{1+p(t)}{k(t)} := \xi.$$

Then we can rewrite Equations (10) and (11) such that

$$g = s_m s \xi^{1-\alpha} - \delta - n, \quad (16)$$

$$g = (1-s_m)s \left[ \frac{1}{\xi} \right]^\alpha - \delta - n. \quad (17)$$

These are two equations in the two unknowns  $g$  and  $\xi$ . Equalizing their right hand sides yields

$$(1 - s_m)s \left[ \frac{1}{\xi} \right]^\alpha = s_m s \xi^{1-\alpha}, \quad (18)$$

$$\frac{1 - s_m}{s_m} = \xi. \quad (19)$$

Obviously, and as expected,  $\xi = p(t)/k(t)$  declines in  $s_m$  because an increase in  $s_m$  means that relatively more machines are accumulated and relatively less automation capital. Plugging (19) into (16) yields the long-run growth rate of the economy as

$$g = s_m \cdot s \left( \frac{1 - s_m}{s_m} \right)^{1-\alpha} - \delta - n = s s_m^\alpha (1 - s_m)^{1-\alpha} - \delta - n.$$

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