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NOTES

A NOTE ON THE IMPLICATIONS OF AUTOMATION FOR ECONOMIC GROWTH AND THE LABOR SHARE

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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; and (iv) automation explains around 14% of the observed decline of the labor share over the last decades in the United States.

Keywords: Automation, Perpetual Economic Growth, Declining Labor Share, Inequality

1. INTRODUCTION

Automation has already taken over many of the tasks for which at least a small amount of labor input had been necessary in the past. 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 diseases and to write simple newsflashes and reports; and driverless cars and lorries are expected to transport passengers and goods in the not so distant future [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

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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 industrial robots as it has been observed between the 1970s and the 2010s implies a reduction of the aggregate labor share by around 0.7 percentage points, which is roughly 14% of the decline reported by Karabarbounis and Neiman (2014) for the United States. Since industrial robots are only a part of all existing automation technologies, the 14% are likely to be a lower bound for the impact of automation on the labor share. Considering the fact that capital income is typically much more unevenly distributed than labor income [Cagetti and De Nardi (2008)], automation could have contributed to the increase in inequality as it has been observed in most developed countries over the last decades [cf. Piketty (2014)].

The main policy conclusion that emanates from our analysis is that it might be useful to design a compensation scheme for the losers of automation technologies. Doing so would distribute the potentially enormous gains of automation more evenly among various parts of the society and thereby help to reduce the resistance to automation. Such a strategy could allow for the timely adoption of automation technologies with the associated positive repercussions on economic growth and well-being, while, at the same time, it would keep inequality in check.

2. THE MODEL

Consider an economy with three production factors, labor, traditional capital (machines, assembly lines, industrial buildings, etc.), and automation capital (robots, 3D printers, devices based on machine learning, etc.). Labor and machines are imperfect substitutes, while automation capital is—by its definition—a perfect substitute for labor. Time t evolves continuously and the workforce grows at the rate of population growth n. Traditional capital and automation capital can be accumulated and, for analytical convenience, they depreciate at rate δ.[1]

The representative firm has access to a Cobb–Douglas production function of the form

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

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, and $A(t) \equiv 1$ refers to the level of technology, which we deliberately normalize to 1. The reason for this normalization is that the potential for perpetual long-run growth due to automation is best illustrated by abstracting from a second engine of growth such as technological progress.[2] Due to perfect competition, the factor rewards are given by

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

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

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where $w(t)$ is the wage rate, $r(t)$ is the interest rate, and the owners of automation capital 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 $I(t)$ such 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. We assume that a share $s_K \in (0, 1)$ of savings is diverted to investment in traditional capital and a share $1 - s_K$ is diverted to investment in automation. This yields the following accumulation equations:

$$\dot{K}(t) = s_K I(t) - \delta K(t) \qquad \text{and} \qquad \dot{P}(t) = (1 - s_K)I(t) - \delta P(t). \tag{3}$$

Output per worker is given by $y(t) = Y(t)/L(t) = [1 + p(t)]^{1-\alpha} k(t)^{\alpha}$, where lowercase letters refer to variables in terms of units per worker, i.e., for any variable $X(t)$ we have that $x(t) = X(t)/L(t)$. Dividing both equations in (3) by $L(t)$ and taking into account the expression for per capita output $y(t)$ allows us to derive the following dynamic system for traditional capital per worker and automation capital per worker, which fully describes the evolution of the economy[3]

$$\begin{aligned} \dot{k}(t) &= s_K s[1 + p(t)]^{1-\alpha} k(t)^{\alpha} - \delta k(t) - nk(t), \\ \dot{p}(t) &= (1 - s_K)s[1 + p(t)]^{1-\alpha} k(t)^{\alpha} - \delta p(t) - np(t). \end{aligned}$$

Dividing by $k(t)$ and $p(t)$, respectively, and imposing constant growth along the balanced growth path (BGP), it can be shown that the economy converges to a situation in which traditional capital per worker, automation capital per worker, and GDP per worker all grow at the common constant rate

$$g = s \cdot s_K^{\alpha} (1 - s_K)^{1-\alpha} - \delta - n. \tag{4}$$

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 (4) 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 (4) is positive, which is the case for plausible parameter specifications (see the numerical section). 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;*

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(*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;*

(*iv*) *an increase in the stock of automation capital reduces the labor share of the economy.*

Proof. Parts (i) and (ii) follow immediately by inspection of (4). For the proof of part (iii), we calculate the derivative of g with respect to s_K:

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

We see that this expression is positive if $\alpha - s_K$ is positive and it is negative if $\alpha - s_K$ is negative. For the proof of part (iv), note that aggregate labor income and the labor share pin down to

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

$$\frac{w(t)L(t)}{Y(t)} = (1-\alpha)\frac{L(t)}{L(t)+P(t)}. \tag{5}$$

We immediately see that the accumulation of automation capital reduces the labor share. ■

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. 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.[4]

Part (ii) of the proposition is explained by the fact that, since the diminishing marginal product of physical capital is overcome by the use of automation, anything that reduces the overall accumulation rate of physical capital—such as capital dilution due to population growth—also reduces 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 literature [see, for example, Jones (1995)], our result is consistent with the available empirical evidence for developed countries throughout the 20th Century [cf. Ahituv (2001), 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 *decrease* in economic growth. However, the reduction in the share of gross investment diverted to traditional capital comes with a corresponding increase in the share of gross investment diverted to automation. The latter would, ceteris paribus, lead to an *increase* in economic growth. If the fraction of gross

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investment diverted to traditional capital is larger (smaller) than the elasticity of final output with respect to traditional capital in the production function, the decrease in growth due to a lower accumulation rate of traditional capital is smaller (larger) than the corresponding increase in the rate of economic growth due to an increase in the accumulation rate of automation capital. Consequently, economic growth is maximized if $s_K = \alpha$.

The intuition for part (iv) is the following. Perfect substitution between labor and automation implies that the wage rate decreases and the capital rental rate increases if the stock of automation capital increases. Since the income that is generated by automation is used to compensate capital owners, this leads to an increase in the capital share and to a decrease in the labor share. Consequently, our framework proposes a complementary way of explaining the empirical finding of a decreasing labor share in most developed countries over the last decades [see Karabarbounis and Neiman (2014), for other important channels].

3. NUMERICAL ASSESSMENT

In this section, we illustrate the effect of automation on economic growth for parameter values inferred from data for the United States [cf. Bureau of Economic Analysis (2004), World Bank (2016)]. 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 rates over the years 2000 to 2013. Furthermore, we use a value of $1/3$ for the elasticity of final output with respect to physical capital (α), which is in line with the data [cf. Karabarbounis and Neiman (2014)]. Finally, we set the rate of depreciation of traditional capital to $\delta_K = 0.0508$ and those of automation capital to $\delta_P = 0.1313$, where the two rates are calculated based upon the depreciation rates suggested by the Bureau of Economic Analysis (2004) for different forms of capital.[5] Regarding the share of investment diverted to traditional capital, s_K, it is difficult to come up with reliable data. We therefore use different values and report the results for $s_K = 0.7$ and $s_K = 0.9$ in Figure 1. Note that for very high (or very low) values of s_K, (4) would become negative and we would end up at a steady state with no growth as in the traditional Solow (1956) model.

In Figure 1, we plot the growth rate of per capita GDP against time from $t = 0$ to $t = 20$. The left diagram refers to the case $\boldsymbol{s_K} = 0.9$ and the right diagram to the case $\boldsymbol{s_K} = 0.7$. We see that the growth rate of per capita GDP converges toward its long-run solution, which is clearly positive. While the solid lines refer to the baseline parameter specification as described above, we also show the impact of an increase in the population growth rate from $n = 0.009$ to $n = 0.02$. The economic growth rate in this case 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.

Finally, we assess the implied impact of the introduction of automation on the labor share by relying on (5). For this purpose, we set $L(t)$ equal to 155 million

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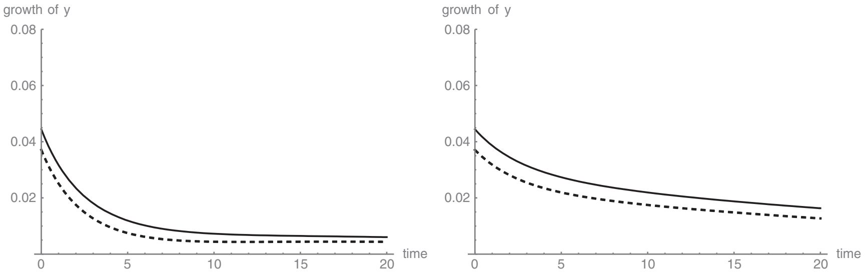

FIGURE 1. Growth rates of per capita output (y) for a low share of investment diverted to automation ($s_K = 0.9$; left side) and for a high share of investment diverted to automation ($s_K = 0.7$; right side). The solid lines represent the original solution, whereas the dashed lines represent the solution with the higher population growth rate.

people, which is the average size of the labor force in the United States between 2000 and 2013 according to the World Bank (2016). Furthermore, we set $P(t)$ equal to the number of industrial robots installed in the United States according to the International Federation of Robotics (2016). This amounts to 164 units per 10,000 workers and can be considered as a lower bound of the stock of automation capital, which also includes other items apart from industrial robots. The reduction of the labor share that our calculations imply is therefore a conservative estimate. Assuming that the number of industrial robots was close to zero at the beginning of the 1970s, our framework implies a decline of the labor share from 66.67% in the 1970s to 65.97% in 2016. This is a decrease by 0.7 percentage points. Since Karabarbounis and Neiman (2014) document a reduction of the global labor share by around 5 percentage points from the early 1970s to the 2010s, our framework explains around 14% of this reduction by automation.

4. CONCLUSIONS

We introduce automation into the original model of Solow (1956) and show that perpetual growth is possible, even in the absence of technological progress and that, consistent with the empirical evidence, the growth rate of per capita output decreases with the growth rate of the population. We use this framework to quantify the impact of automation on the labor share and find that it explains a decline of around 0.7 percentage points, which is 14% of the decline reported by Karabarbounis and Neiman (2014).

Our main policy conclusion derives from the fact that automation has the potential to raise overall living standards, while workers would lose and capital owners would gain. To reduce the anticipated opposition to automation from labor unions and to mitigate the increase in inequality associated with automation, a compensation scheme that supports the losers of automation technologies might therefore be desirable.

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NOTES

1. In the numerical section, we allow for different depreciation rates of the two types of capital and infer these rates from the suggested depreciation rates of the Bureau of Economic Analysis (2004). As far as the quantitative implications are concerned, only the economic growth rate changes with the chosen rates of depreciation, while the impact of automation on the labor share at the steady state is not affected by different rates of depreciation.

2. See Schäfer and Schneider (2014) and Prettner and Strulik (2016) for recent frameworks in which (endogenous) technological progress is the main engine of long-run economic growth.

3. For the detailed steps of the derivations see Appendix A.2 of Prettner (2016), which is an earlier working paper version of this article.

4. Apart from automation, Palivos and Karagiannis (2010) show that a high elasticity of substitution between capital and labor can act as an independent engine of economic growth in the long run. Furthermore, Peretto and Saeter (2013) propose a model in which purposeful R&D increases the elasticity of output with respect to physical capital in a Cobb–Douglas production function. This implies that the production function endogenously converges to an AK-type such that physical capital accumulation is sufficient to generate long-run economic growth.

5. We take the average of the depreciation rates of metal working machinery, machines in special industries, office buildings (including medical buildings), and manufacturing structures as a proxy for δ_K and the average depreciation rates of computers and electronic products in the metal working sector and in special industries as a proxy for δ_P.

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