3

A One-Sector Model of Robotic Immiserization

Jeffrey D. Sachs, Seth G. Benzell and Guillermo Lagarda

3.1 Introduction

The word robot comes from the Czech word "robota", meaning forced labor. Ever since the term's invention by Karl Čapek in his 1920 dystopian science fiction masterpiece R.U.R, it has been associated with ambivalence about the power of automation. The play begins with the general manager of Rossum's Universal Robots discussing the potential of his assembled beings to raise living standards. He predicts that his robot laborers will lower the prices of goods to zero, ending toil and poverty forever. This plan hits a small snag when the robots decide to overthrow their masters and destroy all humans. But was the manager's economic forecast even correct in the first place?

This paper investigates the implications of capital investments, in the form of robots, which allow for production without labor. Our key finding is that an increase in robotic productivity will temporarily raise output, but, by lowering the demand for labor, can lower wages and consumption in

J. D. Sachs
Center for Sustainable Development, Columbia University,
New York, NY, USA

S. G. Benzell
MIT Initiative on the Digital Economy, Boston University, Boston, MA, USA

G. Lagarda (✉)
Inter-American Development Bank and Global Development Policy Center, Boston University, Boston, MA, USA

L. Pupillo et al. (eds.), *Digitized Labor*, https://doi.org/10.1007/978-3-319-78420-5_3

the long run. In what we term a *paradox of robotic productivity*, innovations that increase the productivity of robotic investments can, after a generation, lower robotic and total output, and lower the well-being (lifetime utility) of all future generations. The mechanism for this immiserization is decreased wages of the workers with whom the robots compete. We find this immiserization is most likely when the future is heavily discounted, goods produced by robots are close substitutes for goods created by human labor, and when traditional capital is a more important factor in non-robotic production (so that the reduction of traditional capital has a larger adverse impact on wages). In our richest setting, increases in robotic productivity lower well-being until a threshold is reached. After reaching the threshold, the economy may grow indefinitely.

The fact that a rise in robotic productivity can immiserize future generations may seem paradoxical. After all, higher productivity enables society to produce more output from the same quantity of inputs. If the market response to robotic innovations does not lead to a positive result, this suggests that there may be a role for government intervention. We show this intuition to be correct. Immiserization may be overcome through redistributive policies of the state.

3.2 Literature Review

Even before the birth of modern science fiction, academics and ordinary people have been concerned about the potential downsides of technological growth.[1] The English Luddites of the late eighteenth and early nineteenth centuries famously organized raids and riots against the industrial machines they felt were taking their jobs. In the second half of the nineteenth century, Marx (1992) bemoaned the fact that under capitalism "all methods for raising the social productivity of labor are put into effect at the cost of the individual worker". In the first half of the twentieth century, Keynes (1933) cautioned against overreaction to "technological unemployment", which, while painful for displaced workers, was merely a "temporary phase of maladjustment". Similarly, Schumpeter (1939) championed the "creative destruction" of capitalism, in which older ways of doing work are, not without pain, superseded by advances in technology as new types of more productive work are created.

In the economic prosperity of the postwar era, the views of technological optimists generally held sway. However, recent wage stagnation and growing inequality across the developed world have led economists to take another hard look at technological growth. Autor et al. (2003) Acemoglu and Autor (2011), and Autor and Dorn (2013) trace recent declines in employment and wages of middle-skilled workers to the development of smart machines. Katz and Margo (2014) point to similar *labor polarization* during the early stages of America's industrial revolution. Goos et al. (2010) offer additional supporting evidence for Europe. Sachs and Kotlikoff (2012) present a model in which robots immiserize future generations, a precursor of the models studied in this paper. However, Mishel et al. (2013) argue that "robots" can't be "blamed" for post-1970s US job polarization given the observed timing of changes in relative wages and employment. A literature inspired by Nelson and Phelps (1966) hypothesizes that inequality may be driven by skilled workers more easily adapting to technological change, but generally predicts only transitory increases in inequality.

A potential implication of our model is a decline, over time, in labor's share of national income. US national accounts record a stable percent share of national income going to labor during the 1980s and 1990s. But starting in the 2000s labor's share has dropped significantly. Frey and Osborne (2013) try to quantify prospective human redundancy arguing that over 47% of current jobs will likely be automated in the next two decades. Olsen and Hemous (2014) calibrate a model in which capital can substitute for low-skilled labor while complementing high-skilled labor to explain trends in the labor share of income and inequality.

The lessons of our model are also related to the endogenous growth literature. In Rebelo's (1991) AK model, sustained per capita output growth occurs so long as there are no decreasing returns to scale in production. This model complemented Romer (1990) which included open-ended growth driven by endogenous technological development in the tradition of learning by doing proposed by Arrow (1962).

There are several models that include a potential for welfare-improving intergenerational transfers. Two papers that with mechanisms more similar to this one are Sachs and Kotlikoff (2012) and Benzell et al. (2015). These papers also posit that technological changes may immiserize future generations through the mechanism of reduced wages.

3.3 The Model Framework

The essential quality of robots, as we define them, is that they allow for output without labor. To produce a unit of output from robotic technology, entrepreneurs need only make a capital investment. Innovation in robotic production can therefore change labor's share of national income. In a model with an infinitely lived representative consumer, this is unlikely to have major effects. However, if those earning labor and capital income have different propensities to consume, then a change in labor's share of income can have important effects on saving and investment. We attempt to capture this effect in the simplest possible setting.

The setup is an overlapping generations (OLG) model with two cohorts. This allows for labor's share of income to have a dynamic effect and straightforward generational welfare analysis.

3.3.1 Households

All individuals live for two periods, working, saving and consuming while young, and consuming while old. Workers in this economy maximize a lifetime utility function of the form

$$U_t = \phi u\left(\vec{c}_{1,t}\right) + (1-\phi)u(\vec{c}_{2,t+1}), \tag{3.1}$$

where $\vec{c}_{1,t}$ and $\vec{c}_{2,t+1}$ are vectors of goods consumed by a household in the first and second periods of life, and $u(\cdot)$ is a within-period homothetic utility function. Henceforth, we assume within-period utility is logarithmic, $u(\vec{c}_t) = \ln(v(\vec{c}_t))$, where v is Cobb–Douglas with constant returns to scale. There is no leisure.

A generation maximizes U_t subject to its lifetime budget constraint, which in general may include government taxes and transfers.

$$w_t L_t + G_t = \vec{p}_t \vec{c}_{1,t} + \frac{\vec{p}_{t+1}\vec{c}_{2,t+1}}{1 + [r_{t+1}(1-\tau_t)]}, \tag{3.2}$$

where $\vec{p}_t$ is a vector of prices, w_t is the wage, G_t is the size of government grants to the young, $1 - r_t$ the interest rate, and τ_t is the capital income tax rate. For convenience, define the net income of the young as the sum of their labor income and any government transfer, and the net interest rate of the old as net of the government capital income tax. Thus,

$$w_t^N = w_t L_t + G_t, \tag{3.3}$$

and

$$r_t^N = r_t(1-\tau_t). \tag{3.4}$$

Utility maximization leads to the well-known result that saving, S_t, equals a fixed fraction $(1-\phi)$ of youth income,

$$S_t = (1-\phi)(w_t^N). \tag{3.5}$$

Households allocate savings with perfect foresight between available types of physical assets to maximize returns.

3.4 Production

There are two perfectly competitive types of firms. Time t production of the consumption and investment good with the traditional output technology, $X_{m,t}$, is as follows

$$X_{m,t} = D_{X,t} M_{X,t}^{\epsilon} L_{X,t}^{1-\epsilon}, \tag{3.6}$$

where $M_{X,t}$ is the amount of machines rented by these firms, $L_{X,t}$ is the amount of labor hired, ϵ is a Cobb–Douglas parameter, and $D_{X,t}$ a total factor productivity term. Production by robotic firms is as follows

$$X_{r,t} = \theta_t R_t, \tag{3.7}$$

where $X_{r,t}$ is the output of these firms, R_t is the amount of robots rented by these firms, and θ_t is the robotic productivity. Factor demands for robots, machines, and labor reflect profit maximization

$$\max_{M_{X,t} L_{X,t}} X_{m,t}(M_{X,t}, L_{X,t}) - w_t L_{X,t} - m_t M_{X,t} \tag{3.8}$$

and

$$\max_{R_t} X_{r,t}(R_t) - \rho_t R_t, \tag{3.9}$$

where m_t is the rental rate for machines and ρ_t is the rental rate for robots.

These yield the first order conditions

$$w_t = (1-\epsilon) D_{X,t} M_{X,t}^{\epsilon} L_{X,t}^{-\epsilon}, \tag{3.10}$$

$$m_t = \epsilon D_{X,t} M_{X,t}^{\epsilon-1} L_{X,t}^{1-\epsilon}, \tag{3.11}$$

and

$$\rho_t = \theta_t. \tag{3.12}$$

3.4.1 Households

Utility is logarithmic in consumption of the one good.

$$u(x_t) = \ln(x_t), \tag{3.13}$$

Household demands for consumption and investment satisfy

$$x_{1,t} = \phi w_t^N \tag{3.14}$$

and

$$x_{2,t} = (1 + r_t^N)K_t, \tag{3.15}$$

where K_t is capital of any type owned by the old.

3.4.2 Equilibrium

The total output of the economy is the sum of the outputs of the two types of firms,

$$X_t = X_{m,t} + X_{r,t}. \tag{3.16}$$

The one-sector model is in equilibrium when the market for goods clears,

$$X_t = x_{1,t} + x_{2,t} + S_t, \tag{3.17}$$

the labor market clears,

$$L_{X,t} = L_t, \tag{3.18}$$

the government is balancing its budget,

$$G_t = r_t \tau_t K_t, \tag{3.19}$$

and the market for investments clears,

$$S_t = K_{t+1} = M_{X,t+1} + R_{X,t+1}, \tag{3.20}$$

as capital depreciates fully each period.

Finally, investment seeks maximum returns in the subsequent period with perfect foresight. Here we are only interested in the case where robots are productive enough to be used, so investment must equalize the rate of return of both forms of capital. Therefore,

$$1 + r_t = m_t = \rho_t = \theta_t. \tag{3.21}$$

3.4.3 Equilibrium Analysis

Consider the case where $D_{X,t} = 1$ and $L_t = 1$ in all periods.

Combining first order equations yields

$$w_t = (1 - \epsilon)\frac{e}{\theta_t}^{\frac{1}{1-\epsilon}} \tag{3.22}$$

Note that a rise in robot productivity reduces the wage. The reason is that higher θ shifts investment from machines into robots. This lowers the capital-labor ratio in X_m firms, decreasing the marginal productivity of workers. The wage is not influenced by the capital stock, because both the quantity of labor and the interest rate are fixed by factors outside the traditional firms. This in turn fixes the amount of capital in traditional firms and therefore the wage.

We can write the indirect utility function in terms of θ_t and θ_{t+1}. Ignoring constant terms, and assuming no transfers ($G_t = \tau_t = 0$) we have

$$U_t = \ln w_t + (1 - \phi)\ln(1 + r_{t+1}), \tag{3.23}$$

or equivalently,

$$U_t = \frac{-\epsilon}{1 - \epsilon}\ln\theta_t + (1 - \phi)\ln\theta_{t+1}. \tag{3.24}$$

Notice that robot productivity has two opposing effects on lifetime utility. High θ_t lowers the wage while high θ_{t+1} raises the returns to saving. The negative wage effect tends to dominate the saving effect when the capital share of income (ϵ) in traditional firms is large, because this measures the importance of machines in complementing the labor or workers. Immiserization is also more likely when the discount rate ϕ is higher, because a high ϕ means that the utility value of higher returns to saving is low.

Consider a one-step permanent rise of θ at time T. That is for $t < T$, $\theta_t = \theta^L$ and for $t \geq T, \theta_t = \theta^H > \theta^L$. The lifetime utility of an individual born in t is

for $t < T - 1$

$$U_t = \frac{-\epsilon}{1 - \epsilon}\ln\theta^L + (1 - \phi)\ln\theta^L, \tag{3.25}$$

when $t = T - 1$

$$U_t = \frac{-\epsilon}{1-\epsilon}\ln\theta^L + (1-\phi)\ln\theta^H, \tag{3.26}$$

and if $t > T - 1$

$$U_t = \frac{-\epsilon}{1-\epsilon}\ln\theta^H + (1-\phi)\ln\theta^H. \tag{3.27}$$

The rise in robot productivity in period T must raise the welfare of generation $T - 1$. For that generation, the rise of robot productivity was too late to impact their wage. However, the return on their saving is increased by the rise in robotic productivity in period T. Generation $T - 1$, in other words, will enjoy high wages when young and high retirement income when old. Generations T and after will not be so lucky. For them, the positive effect of better robots is at least partially offset by lower wages.

An increase in robotic productivity will induce long-run immiserization[2] as long as

$$\frac{\epsilon}{1-\epsilon} > (1-\phi). \tag{3.28}$$

If Eq. 3.28 holds, the wage effect dominates and leads to a decline in lifetime utility. Only a single generation benefits from the rise of robot productivity, specifically the generation born in the period before the improvement in robot productivity. That generation benefits from higher returns to saving without incurring the negative shock of lower wages.

3.4.4 Ensuring That All Generations Benefit from the Rise in θ

Could a managed rise of robots lead to a better long-run outcome? It is clear that markets alone are not sufficient to ensure that a rise of robot productivity raises the well-being of future generations. However, it seems likely that a pure rise in productivity, by pushing out the production possibility frontier, can be made into a rise in lifetime utility for all generations with the right kind of government intervention. To insure a better outcome, the income of the young should be augmented by redistribution from the old.

Here's how to turn the robotics innovation in time T into a rise in well-being for all generations from time $T - 1$ onward.

In every period T and after, the government levies a tax on the capital income of retirees and transfers the proceeds as a grant G_t to the young.

Let the government set the grant equal to the decline of the wage caused by the rise of θ. Let w^H be the market wage associated with θ^H and w^L be the market wage associated with θ^L. Then necessarily, $w^L > w^H$. The grant mechanism will function as follows: For $t > T - 1$

$$G_t = w_t^L - w_t^H. \tag{3.29}$$

To pay for this grant, the government levies a capital-income tax at rate τ_t on the old in each period. With saving S_t, pre-tax capital income is given by $\theta^H S_t$. Therefore, the tax rate should be set such that for $t \geq T$

$$G_t = \left(\theta^H - 1\right)\tau_t K_t. \tag{3.30}$$

Of course, savers anticipate this capital income tax and plan their inter-temporal spending decisions accordingly. Instead of earning a rate of return θ^H, savers will earn a net-of-tax rate of return $\left(1 + r_{t+1}^N\right) = 1 + (\theta^H - 1)(1 - \tau_t)$. Because of their logarithmic preferences this change in rate of return does not change their saving behavior. The indirect lifetime utility function can be rewritten in terms of youth net-of-transfer income w_t^N and r_{t+1}^N. Since policy fixes the disposable wage at w_t^L we have, ignoring constant terms,

$$U_t^L = \ln(w_t^L) + (1 - \phi)\ln(1 + r_{t+1}^N). \tag{3.31}$$

Every generation will be better off when θ rises to θ^H, as net-of-tax lifetime budget constraints must be larger than when θ^L.

When θ rises, it is easy to see that X_t rises instantaneously as well. This is because the level of capital is unchanged, but its productivity has increased. Now, consider total output from the perspective of factor income. Since there are no profits, $X_{r,t} = \theta R_t$ and $X_{m,t} = w_t + \theta M_t$, we have that $X_t = w_t + \theta(R_t + M_t) = w_t + \theta S_{t-1}$. By Eq. 3.5, S_t depends only on the net income of the young w_t^N. The transfer system keeps the disposable wage equal to w_t^L, so saving S_t also remains unchanged when θ rises. When θ rises, the overall rise of X_t ensures that $w_t^H + \theta^H S_t > w_t^L + \theta^L S_t$. Therefore, $w_t^H - w_t^L + \theta^H S_t > \theta^L S_t$. Since $w_t^L - w_t^H$ equals G_t, which is also equal to $(1 + \left(\theta^H - 1\right)\tau_t)S_{t-1}$, we find that $\left(1 + \left(\theta^H - 1\right)\tau_t\right)S_{t-1} > \theta^L S_t$. Hence, $(1 + r_{t+1}^N) = (1 + (\theta^H - 1)\tau_t) > \theta^L$.

This reasoning establishes a key result. By taxing the capital of the old, and transferring the proceeds to the young, the government keeps the net income of the young unchanged while the net-of-tax rate of return on saving is higher. Therefore, the rise of robot productivity to θ^H combined with the fiscal transfer system raises the well-being of all generations compared with the utility when productivity equals θ^L.

The result is important in light of discussions as to whether robotics will necessarily raise or lower well-being. The answer is that higher productivity is a potential gain for all generations, but only if government undertakes redistributive policies to ensure that indeed all generations benefit. Without such redistribution, it is possible, we have seen, that the robotics innovation improves the well-being of just one generation, while lowering the lifetime well-being of all future generations.

3.5 Conclusion

The rise of the robots is already creating major disruption in labor markets, essentially turning production processes more capital intensive. When robots are close substitutes for production by labor and machinery, the demand for labor is likely to decline, threatening a decline of wages, saving, and economic well-being of current and future generations. We have qualified that intuition, however. Government redistribution can ensure that a pure productivity improvement raises well-being of all generations. In the example shown in the paper, government taxes the capital owned by retirees and distributing the proceeds to young workers.

Notes

1. This section draws on Benzell et al. (2015).
2. On the other hand, a reduction in long-run national consumption can only occur if θ increases above 1. This is because the golden rule (long-run consumption maximizing) level of saving, given constant L and 100 percent depreciation is that which brings long-run interest rates equal to 1. In cases where θ increases from a level below 1 to a level closer to but still below 1, long-run consumption will increase although welfare may decrease.

References

Acemoglu, Daron, and David Autor. 2011. "Skills, Tasks and Technologies: Implications for Employment and Earnings." *Handbook of Labor Economics* 4: 1043–1171.

Arrow, K. 1962. "The Economic Implications of Learning by Doing." *The Review of Economic Studies* 29 (3): 155.

Autor, David H., and David Dorn. 2013. "The Growth of Low-Skill Service Jobs and the Polarization of the US Labor Market." *The American Economic Review* 103 (5): 1553–1597.

Autor, David H., Frank Levy, and Richard J. Murnane. 2003. "The Skill Content of Recent Technological Change: An Empirical Exploration." *The Quarterly Journal of Economics* 118 (4): 1279–1333.

Benzell, Seth G., Laurence J. Kotlikoff, Guillermo LaGarda, and Jeffrey D. Sachs. 2015. *Robots Are Us: Some Economics of Human Replacement*. No. w20941. National Bureau of Economic Research.

Frey, Carl Benedikt, and Michael A. Osborne. 2013. "*The Future of Employment*." Oxford Martin.

Goos, Maarten, Alan Manning, and Anna Salomons. 2010. *Explaining Job Polarization in Europe: The Roles of Technology, Globalization and Institutions*. No. dp1026. Centre for Economic Performance, LSE.

Katz, Lawrence F., and Robert A. Margo. 2014. "Technical Change and the Relative Demand for Skilled Labor: The United States in Historical Perspective." In *Human Capital in History: The American Record*, pp. 15–57. Chicago: University of Chicago Press.

Keynes, John Maynard. 1933. "Economic Possibilities for Our Grandchildren (1930)." In *Essays in Persuasion*, pp. 358–373. New York: Harcourt Brace.

Long, Tony. 2017. "Jan. 25, 1921: Robots First Czech In." *WIRED* [online]. Available at: http://www.wired.com/2011/01/0125robot-cometh-capek-rur-debut/.

Marx, Karl, and Ben Fowkes. 1992. "A Critique of Political Economy. Vol. 1 of Capital."

Mishel, Lawrence, John Schmitt, and Heidi Shierholz. 2013. "Assessing the Job Polarization Explanation of Growing Wage Inequality." Working Paper, Economic Policy Institute.

Nationalarchives.gov.uk. 2017. The National Archives Learning Curve | Power, Politics and Protest | Luddites [online]. Available at: http://www.nationalarchives.gov.uk/education/politics/g3/.

Nelson, Richard R., and Edmund S. Phelps. 1966. "Investment in Humans, Technological Diffusion, and Economic Growth." *The American Economic Review* 56 (1/2): 69–75.

Olsen, Morten, and David Hemous. 2014. "The Rise of the Machines: Automation, Horizontal Innovation and Income Inequality." In *2014 Meeting Papers*, no. 162. Society for Economic Dynamics.

Rebelo, Sergio. 1991. "Long-Run Policy Analysis and Long-Run Growth." *Journal of Political Economy* 99 (3): 500–521.

Romer, Paul M. 1990. "Endogenous Technological Change." *Journal of Political Economy* 98 (5, Part 2): S71–S102.

Sachs, Jeffrey D., and Laurence J. Kotlikoff. 2012. *Smart Machines and Long-Term Misery*. No. w18629. National Bureau of Economic Research.
Schumpeter, Joseph Alois. 1939. *Business Cycles*, vol. 1. New York: McGraw-Hill.