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ABSTRACT

Are smarter machines our children's friends? Or can they bring about a transfer from our relatively unskilled children to ourselves that leaves our children and, indeed, all our descendants – worse off?

This, indeed, is the dire message of the model presented here in which smart machines substitute directly for young unskilled labor, but complement older skilled labor. The depression in the wages of the young then limits their ability to save and invest in their own skill acquisition and physical capital. This, in turn, means the next generation of young, initially unskilled workers, encounter an economy with less human and physical capital, which further drives down their wages. This process stabilizes through time, but potentially entails each newborn generation being worse off than its predecessor.

We illustrate the potential for smart machines to engender long-term misery in a highly stylized two-period model. We also show that appropriate generational policy can be used to transform win-lose into win-win for all generations.

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Introduction

Can mechanization lead to misery for workers? The idea is an old one, dating at least to the Luddites. The fear is that machines substitute for workers and drive down their wages. The retort is that machines make workers more productive and drive up their wages. Economists have long ridiculed the Luddites based on a stubborn fact – average real wages grow in line with average labor productivity.

But what if the Luddites are now getting it right -- not for labor as a whole, but for unskilled labor whose wages are no longer keeping up with the average? Indeed, what if machines are getting so smart, thanks to their microprocessor brains, that they no longer need unskilled labor to operate?

Evidence of this is everywhere. Smart machines now collect our highway tolls, check us out at stores, take our blood pressure, massage our backs, give us directions, answer our phones, print our documents, transmit our messages, rock our babies, read our books, turn on our lights, shine our shoes, guard our homes, fly our planes, write our wills, teach our children, kill our enemies, and the list goes on.

Yes, technology has always been changing. But today's change is substituting for, not complementing unskilled labor. Yesterday's horse-drawn coaches were replaced by motorized taxis. But both required a human being with relatively little human-capital investment – a cabbie -- to drive them. Tomorrow's cars will drive themselves, picking us up, dropping us off, and returning home all based on a few keystrokes. This will make cabbies yet another profession of the past.

Although smart machines substitute for unskilled workers, they are designed and run by skilled workers. So it's no surprise that the incomes of skilled workers have risen relative to those of unskilled workers. One indicator is the U.S. college-wage premium, which has increased from around 40 percent in 1999 to more than 80 percent today.[1] Another is the dramatic growth in recent years in income inequality, documented by Atkinson, Piketty, and Saez (2011), most of which they trace to "an unprecedented surge in top wage incomes." The top 10 percent of U.S. households now receive 50 percent of all income – up from 35 percent four decades ago.[2]

Gordon (2009) also presents evidence documenting recent increases in wage inequality, including an increase in the share of wage income earned by the top 10 percent higher earners – from roughly 26 percent in 1970 to 36 percent by 2006.[3] He also reports a close-to 10 percentage-point fall in labor's share of national income since the early 1980s. This decline in labor's overall share may also reflect accelerating growth in machine brainpower. Machines, after all, are a form of capital, and the higher income they earn based on better machine brains may show up as a return to capital, not labor income.

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[1] http://www.clevelandfed.org/research/commentary/2012/2012-10.cfm

[2] Atkinson, Piketty, and Saez (2011). Much of this inequality has occurred at the very top of the income distribution. Since the early 70s, incomes of the top 1 percent have grown seven times faster han the remaining 99 percent. As a result, the top 1 percent have captured three fifths of all income growth, with their income sharing rising from 10 to 25 percent.

[3] Gordon (2009) argues that wage inequality is overstated because the prices of goods and services consumed by high-wage earners, particularly housing prices in neighborhoods catering to the rich, have risen more rapidly than those consumed by low-wage workers. But the fact that the high-wage workers choose to purchase more expensive goods and services doesn't bear on our paper's concern and our model's implication, namely that the marginal products of low- and high-skilled workers are diverging.

Brainier machines pose not just an economic threat to the welfare of today's unskilled workers. They also pose a threat to tomorrow's workers, whether skilled or unskilled. Obtaining skills takes time studying in school and learning on the job. Thus skilled workers are disproportionately older workers. Hence, when machines get smarter, older workers get richer. And since older workers as well as retirees disproportionately own the machines as well as the inventions that enhance the machines, machine-biased productivity improvements effects a redistribution from younger, relatively unskilled workers to older relatively skilled workers as well as retirees.

This too is evident in the data, though the trends in income by age have not been analyzed in as much detail as income by education level. The Census Bureau publishes median income by age for the years 1947 to 2011.[4] If we compare the median incomes of men aged 45-54 with men aged 25-34, we find that the ratio of relative income of the older cohort has risen significantly. In 1950, the income of older men was 4 percent more than their younger counterparts. In 1970, the gap was 11 percent. By 2011, the income of older men was 41 percent above the income of the younger men. For women, the trend is less apparent, with the ratio of income rising from 0.92 in 1950 to 1.15 in 1970 but then declining slightly to 1.11 in 2011. This difference may reflect that fact that men were more exposed to the downsizing of employment in manufacturing as machines replaced less-skilled workers.

[4] http://www.census.gov/hhes/www/income/data/historical/people/, Table P8

As shown below, in an admittedly highly stylized life-cycle model, the general equilibrium effects of this generational redistribution can transform enhancements in machines into very bad news not just for contemporaneous young generations, but for all future generations. The model treats all young workers as unskilled agents who invest their savings in the acquisition of both skills and machines. When today's machines get smarter, today's young workers get poorer and save less. This, in turn, limits their own investment in themselves and in machines. The knock-on effect here is that the economy ends up in all future periods with less human and physical capital, which further depresses the first-period wages of subsequent young generations. Although the skilled wage premium and the return to capital rises, the net impact of smartening up today's machines is a reduction in the lifetime wellbeing of today's and tomorrow's new generations. In short, better machines can spell universal and permanent misery for our progeny *unless* the government uses generational policy to transform win-lose into win-win.

In focusing on the men vs. machine fight, we don't claim that this is the only or even necessarily the primary factor underlying the relative decline in low-skilled U.S. wages. Clearly, increased competition with low-skilled workers in China, India, and other emerging economies is also a part of the story.[5] The more these workers produce, the more they reduce the global prices of low-skilled-intensive traded products, which

[5] Michael Spence (2011) argues that globalization has raised job prospects for U.S. skilled workers and lowered them for unskilled workers. Fehr, Jokisch, Kotlikoff (2008) show that catch-up productivity growth in China, India, and other developing countries could exacerbate wage inequality. Catch-up productivity growth refers to uniform growth in the productivity of workers at all skill levels. But since developing countries are relatively abundant in low-skilled workers, this catch up process brings about an increase in the worldwide endowment of unskilled relative to skilled workers.

translates into lower wages for low-skilled workers across the globe. This is the standard factor-price equalization mechanism. But improved communication technologies have permitted U.S. companies to directly substitute foreign for domestic workers via offshoring – hiring workers abroad at lower wages to produce what their American workforces would otherwise make.

This spatial disaggregation of the value chain has been particularly significant in manufacturing, which employed around 30 percent of the U.S. workforce in 1950, but less than 10 percent today. This said, the fight with foreign workers and machines for domestic jobs, particularly low-skilled jobs, are not necessarily separate battles. If machines and low-skilled workers are very close substitutes in production, the Chinese "worker" taking an American's job could well be a smart machine installed on the floor of a Chinese factory.

Modern economics' reluctance to embrace the Luddite view reflects a long record in industrial countries of real wage growth even among the least skilled. It also reflects the profession's reliance on the mathematically convenient Cobb-Douglas production function in which different inputs enter the function symmetrically. With this functional form, technical change makes all inputs more productive.

But economists' mathematical formulations of production are just that – formulations. No mathematical description fully captures the means of production for any single firm let alone an entire economy consisting of millions of firms. Nor can we rely on technology changing in a uniform manner through time. In the model we now present, machines and unskilled workers produce an intermediate product that is then combined with skilled labor to produce a final output. As long as machines and unskilled workers are relatively substitutable compared with the intermediate product and skilled workers, a rise in machine productivity can substitute for unskilled labor, thereby reducing its wage. As a result, the improvement in machine productivity in turn creates consequences for the contemporaneous and future young that are remarkably bad for the chosen parameters.

Previous Literature

Our simple model, which places the potential dynamic knock-on effects of machine competition in stark relief, complements the ground-breaking work of Zeira (1988) in which labor and capital are used in fixed proportions to produce intermediate inputs needed for final production. Technical change in Zeira's model entails adopting more capital-intensive technologies for these inputs. Countries with higher wages adopt such technologies over time. Those with lower wages do not. Zeira's model represents a very deep contribution to understanding differential growth across countries. But it doesn't distinguish between low- and high-skilled workers or consider the intergenerational redistribution that arises from the smartening of machines.

Zuleta (2004, 2008, and 2012) endogenizes technical change in a series of rich and very interesting papers in which bequests play a major role. Under the right assumptions, his OLG model also produces long-run output declines as a result of technological progress that adversely affects capital accumulation.

Brynjolfsson and McAfee (2012), in their acclaimed book *Race Against Machines*, also emphasize that smart machines can wreck havoc on the wellbeing of workers, although they stress that white collar as well as blue collar jobs and wages are threatened.

The Model

The model is a variant of the standard two-period overlapping generation (OLG) model. The production function depends on three inputs: machines M, unskilled labor L, and skilled labor S. Specifically, gross output Q is a constant elasticity of substitution (CES) production function of the economy-wide stocks of M, L, and S:

(1) $Q = Q[N(uM,L), S]$

M and L combine in a CES production function with elasticity εML to produce an intermediate product N, and N and S combine in a CES production function with elasticity εSN to produce the final output Q. The parameter u is a parameter measuring the technical efficiency of machinery. We examine whether a rise in u, a pure technical advance, can reduce economic wellbeing, an outcome we refer to as "immiserizing productivity."

In any period, M, L, and S are determined by past investments and are fully employed. Competitive firms hire M, L, and S to the point where their marginal products (denoted as Q_i for i = M, L, and S) equal their market wages:

(2) $Q_i = W_i$

Consider the effect of a rise on u on the wage of unskilled workers, $Q_L = W_L$. Specifically, let us determine $d\ln(Q_L)/d\ln(u)$. A bit of algebra reveals that:

(3) $d\ln(Q_L)/d\ln(u) = [\varepsilon SN - \theta\varepsilon ML]/\varepsilon ML$,

where θ is the share of skilled labor in the economy, equal to $(Q_S * S)/Q$. We see that a rise in machine productivity reduces the unskilled wage if $\varepsilon ML > \varepsilon SN/\theta$. Immiserizing productivity is more likely if:

- Substitutability of machines and unskilled labor is high (εML large)
- Substitutability of intermediate goods and skilled labor is low (εSN small)
- The share of skilled labor in final output is high (θ high)

Note that immiserizing productivity is not possible for a Cobb-Douglas production function or indeed for any aggregate CES production function in which εML = εSN. In those cases, a rise in machine productivity necessarily raises the wage of unskilled labor.

We also note that:

(4) $d\ln(Q_S)/d\ln(u) = (1-\theta)(1-\alpha)/\varepsilon SN > 0$,

where α is the share of unskilled labor in the production of N. We see from (4) that skilled workers always benefit from a rise in machine productivity, under the separability assumptions in (1).

Now let us put this production framework into a standard two-period overlapping-generations (OLG) model. We assume that the labor force is fixed across generations at the constant level L. Each individual lives for two generations, young (Y) and old (O). When young, each individual supplies one unit of unskilled labor, and earns wage income $W_L = Q_L$. This wage income is divided between saving Σ and consumption CY:

(5) $W_L = \Sigma + CY$

Saving, in turn, is divided between investments in next-period machinery M and skills S:

(6) $\Sigma_t = M_{t+1} + S_{t+1}$

We assume that both M_t and S_t last for exactly one period. The return on investing in M and S is Q_M and Q_S respectively. The old generation in period t+1 fully consumes its income:

(7) $CO_{t+1} = W_L - CY_t + (Q_M)_{t+1} M_{t+1} + (Q_S)_{t+1} S_{t+1}$

If young savers in period t have perfect foresight regarding the marginal products of M and S in period t+1, they will invest in M_{t+1} and S_{t+1} so as to equalize the marginal products of M and S:

(8) $(Q_M)_{t+1} = (Q_S)_{t+1} = R_{t+1}$,

where R_{t+1} is the gross rate of return to saving in period t. Equation (7) can then be re-written as a familiar inter-temporal budget constraint, in which the present discounted value of lifetime consumption is equal to the income of the (unskilled) worker when young:

(9) $W_L = CY_t + CO_{t+1} / R_{t+1}$

A member of generation t maximizes a two-period utility function $U_t = U(CY_t , CO_{t+1})$ subject to the budget constraint. For simplicity, we use the log-utility function:

(10) $U_t = \beta \ln (CY_t + (1- \beta) \ln(CO_{t+1})$

This utility function results in the familiar result that consumption when young is a fixed multiple of W_L:

(11) $CY_t = \beta W_L$ and $CO_{t+1} = (1- \beta)R_{t+1}W_{Lt}$

Since saving is given by $\Sigma = W_L – CY = (1- \beta)W_L = (1- \beta)Q_L$ we can plug (11) back into (9) to yield the following expression for the utility of generation t:

(11) $U_t = \text{constant} + \ln(Q_L) + (1-\beta) \ln R_{t+1}$

We now show that a rise in machine productivity can reduce generational welfare for the young. The rise in u leads to a fall in Q_L and a rise in R_{t+1}. The wellbeing of the young is affected in two offsetting ways: by a fall in labor income and by a rise in the return on saving. In principle, U_t can either rise or fall when productivity increases. The larger is β (the more impatient is the household) the more likely is immiserizing productivity.

Suppose that Q_L declines as the result of the rise in machine productivity. This is not the end of the story. Since saving is a fixed share of the wage, saving will also decline, causing a decline in M+S. This in turn will further lower next period's output.

The economy will reach a new equilibrium, at a lower level of M, S, and unskilled wage W_L.

When we examine the dynamic effects of a rise in u we must distinguish between anticipated and unanticipated increases in u. Suppose that u is constant until period t, and then rises permanently to u+Δ for all i ≥ t. If the rise in u is *anticipated* as of period t-1, savers in period t-1 will shift their savings of M and S to keep $Q_M = Q_S$ in period t. If savers in period t-1 do not anticipate the rise in u in period t then Q_M will exceed Q_S in period t.

An illustration

Consider the specific production function $Q = \pi N^a S^{(1-a)}$, N = L + uM, and 0 < a < 1. The term π is total factor productivity in the production of Q. L and M are perfect substitutes in the production of N, that is εML = ∞ and immiserizing productivity is guaranteed. For given M and S, a rise u necessarily lowers Q_L. Specifically, $d\ln Q_L/du = (a-1)M/(L+uM) < 0$.

As an illustration, we select L= 1, a = 0.5, β = 0.5, π = 10, and u = 1, which implies a share of income going to all labor (unskilled plus skilled) of 68 percent. Since the technology is constant, there is no long-term growth in the economy. The baseline equilibrium values of key variables are shown as Periods 1 and 2 in Table 1. We suppose that u unexpectedly and permanently increases from the baseline value 1 to a new permanent value of 10 beginning in period 3.

We see in Table 1 the effects of the rise in u. In the top third of the table we consider the case of an unanticipated rise in u. This means that investors in period 2 do not realize that u will rise as of period 3. The action therefore begins only in period 3.

In the third period, M and N are unchanged as a result of the productivity shock, as they were determined by the saving decisions of the young in the first period. The current wage of unskilled workers (i.e. the earnings of the young of generation 3) declines from 5.10 to 2.53 as the result of the rise in u. The returns on M and S both rise, and the old generation (that owns both M and S) experiences a boom in income while the young generation experiences a bust. Consumption of the old rises while consumption and saving of the young declines. This pushes down the future capital stocks of M and S. By period 5 the economy reaches a new equilibrium characterized by lower wages, lower skills, lower M, and higher total output than in the baseline. The ratio of earnings of skilled workers relative to unskilled workers, W_S/W_L, is permanently raised from 1 to 10.

Let us look at the implications for lifetime utility across generations. The lifetime utility of generation 2 (which reaches old age in period 3 as productivity rises) soars. This generation benefits from high returns to both M and S. The utility of generation 3 is slightly below that of generation 1, as wages have declined while the returns on saving have increased. Yet the utility of generations 4 and later are considerably lower than the baseline utility. All generations other than generation 2 lose from the rise in productivity!

If the rise in productivity in period 3 is already anticipated in period 2, the dynamics are slightly different. In essence, the trajectory to the new equilibrium is accelerated. Savers in period 2 allocate more saving to machines and less to skills. This means that the wage of unskilled workers in period 3 is even *lower* than in the unanticipated case because there are more machines to substitute for unskilled labor when the rise in u is anticipated. The utility of generation 3 falls harder and faster. Once again, only generation 3 (the generation that is old when u rises) wins, while all of the succeeding generations are worse off.

Intergenerational Policy to the Rescue

There is something paradoxical about a pure rise in productivity that leaves all generations but one worse off. After all, machines can now do more on behalf of humanity than they could before the rise in u. It should be possible, in principle, to make all generations better off as a result of the pure increase in machine productivity.

Indeed it is. The key is to tap some of the windfall of the older generation in period 3, and share it with the young generation and with succeeding generations. Intergenerational fiscal policy can do the trick. Here's how.

Let us return to the case of an unanticipated rise in u. In period 3, when productivity unexpectedly rises, the government also unexpectedly imposes a wealth tax on the old. Specifically, the government takes an amount $M^G < M$ of the machinery via a wealth levy, while the balance of machinery, $M^P = M - M^G$, is left in the hands of the old of generation 2. The government chooses M^G so that all generations have higher utility than in the baseline. In the illustration in Table 1, the government taxes away approximately 18 percent of M^P (M^G is 0.25 of the total stock M = 1.42).

The government's income in period 3 is equal to Q_{M3}*M^G. The government transfers the amount (Q_{M3} - 1)*M^G to the young of generation 3, whose income is now W_L + T, where T is the transfer payment made by the government. The government also saves and reinvests the sum M^G for the next period. The generation-3 youth make their saving and investment decisions in the knowledge that the government will also be investing in the machinery sector. Total machinery in each period will then be the sum of privately held machinery, M^P, and the government-owned machinery, M^G. In each subsequent period, the government transfers an amount (Q_M – 1)*M^G to the current young generation out of the income that it receives on the income from the government-owned machinery, and it reinvests the sum M^G to maintain a constant level of M^G.

It is easy to illustrate that this kind of tax-ownership-and-transfer system makes it possible to improve the utility of *all generations* as a result of the rise in u. In the example in Table 1, the utility of generation 1 is 5.76, and this rises to 10.48 for generation 2, leaving generation 2 better off than the baseline despite the capital levy. Future generations are even better off then generation 2 as a result of the government's transfer program.

Conclusion

Even if economists have been reluctant to view machines, be they drones or microprocessors, as dangerous competitors, those whose jobs have been lost to machines are facing a terrible time finding employment that pays a decent wage. In contrast, those who own the machines or have the skills to design and run the machines are having no trouble capitalizing on the mechanized misery of the masses.

Our point can be simply summarized. Suppose that an innovation in machine technology (e.g. improved software) raises machine productivity in a manner that indeed reduces the marginal productivity of low-skilled workers while raising the marginal productivity of high-skilled workers. This not only increases the income gap between skilled and unskilled workers, but also has a generational effect, raising the incomes of the older generation while lowering the income of the young. This effect occurs because the old have accumulated physical and human capital, while the young are endowed with unskilled labor. The generational redistribution has a knock-on effect on national saving. Income shifts from young savers to older dis-savers, thereby depressing the national saving rate and the future stock of capital.

The effect can be strong enough, if the parameter values are within a certain range, to reduce the incomes not only of today's young workers but also of future generations. The fall in today's saving rate means that the next generation will have even lower wages than today. The economy will reach a new equilibrium in which the technological advance has raised the wellbeing of today's older generation while lowering the wellbeing of today's young generation and of all future generations!

The Luddites may, therefore, have had a point after all. Advances in machine productivity can indeed immiserize today's young and future generations. But does this mean that we should smash the machines? Here we can benefit from a bit more insight. Instead of smashing the machines (or more prosaically, preventing their deployment), we can instead use inter-generational tax-and-transfer policy. When the older generation enjoys a windfall from the advance of technology, the government can tax some of that windfall, and then use the proceeds to improve the wellbeing of today's youth and of future generations. With the right choice of tax-and-transfer policies, all generations can benefit from the advance in technology, while under *laissez faire*, only today's older generation benefits, and at the expense of all other generations.

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Table 1. Dynamics of a Rise of Machine Productivity
(Unanticipated and anticipated cases)

Period	1	2	3	4	5	6
Unanticipated						
U	1	1	10	10	10	10
M	1.13	1.13	1.13	0.72	0.57	0.57
S	1.42	1.42	1.42	0.55	0.44	0.44
W_L	5.10	5.10	2.53	2.03	2.03	2.03
Q	18.11	18.11	51.88	27.72	22.66	22.66
U generation t	5.76	11.22	5.70	4.58	4.58	4.58
Anticipated						
U	1	1	10	10	10	10
M	1.13	1.13	1.49	0.57	0.57	0.57
S	1.42	1.42	1.06	0.45	0.45	0.45
W_L	5.10	5.10	2.03	2.03	2.03	2.03
Q	18.11	18.11	53.84	22.66	22.66	22.66
U generation t	5.76	11.50	4.58	4.58	4.58	4.58
Unanticipated With Fiscal Transfers						
U	1	1	10	10	10	10
M	1.13	1.13	1.13	2.54	2.13	2.15
MP	1.13	1.13	0.88	1.88	1.90	1.90
MG	0	0	0.25	0.25	0.25	0.25
S	1.42	1.42	1.42	2.01	1.74	1.75
W_L	5.10	5.10	2.53	2.03	2.03	2.03
Transfer Pay	0	0	6.07	5.10	5.15	5.15
Q	18.11	18.11	51.88	27.72	22.66	22.66
U generation t	5.76	10.48	19.32	16.25	16.40	16.40