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# Robot Arithmetic: New Technology and Wages[†]

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*Existing economic models show how new technology can cause large changes in relative wages and inequality. But there are also claims, based largely on verbal expositions, that new technology can harm workers on average or even all workers. This paper shows—under plausible assumptions—that new technology is unlikely to cause wages for all workers to fall and will cause average wages to rise if the prices of investment goods fall relative to consumer goods (a condition supported by the data). We outline how results may change with different assumptions.* (*JEL* D31, G31, J22, J24, J31, O31, O33)

There are widespread concerns among commentators from many different backgrounds (including science, philosophy, business, as well as economics; see, for example, Brynjolfsson and McAfee 2014; Ford 2015; Frey and Osborne 2017; Susskind and Susskind 2015; Bostrom 2014; Executive Office of the President 2016; Stone et al. 2016) about the current and likely future impact of new technology (mostly robots and artificial intelligence) on the demand for labor. There is also a growing empirical literature on the impact of new technology and robots on the labor market (Autor and Dorn 2013; Goos, Manning, and Salomons 2014; Graetz and Michaels 2015; Acemoglu and Restrepo 2017).

Fears about the impact of new technology on workers are not new, although the technology feared has varied over time (National Commission on Technology, Automation, and Economic Progress 1966; Autor 2015). Past fears proved unfounded, but it is argued (not for the first time) that "this time is different," and that the past impact of technologies can be no guide to the future impact. But many of the current analyses of the likely impact of new technology on workers rely on verbal or partial equilibrium analysis without a formal model of the economy as a whole. The risk is that the conclusions are not based on underlying consistency of reasoning. This paper is about the conditions in which new technology can or cannot harm workers, and is motivated by the belief that the existing literature largely consists of a set of special models while this paper aims for results that are as general as possible.

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The existing economics literature provides examples of models in which new technology can cause large changes in relative wages and increases in inequality (e.g., Acemoglu and Autor 2011). And if capital is regarded as fixed, then it is simple to write down a constant returns to scale production function in which wages for all workers fall. If the production function is $F(L, K, \theta)$ where $\theta$ is new technology, and $\frac{\partial F}{\partial \theta} > 0$ (so new technology raises output) but $\frac{\partial^2 F}{\partial L \partial \theta} < 0$, then the marginal product of labor and the wage falls with new technology.

It has proved much harder to write down models with endogenous capital in which wages fall. For example Acemoglu and Restrepo (2017) identify what they call the "productivity effect" that causes wages to rise with new technology in their model once capital is endogenous. But their model has one type of labor and one good (which can be a capital or consumption good) and a very particular form of new technology, leaving open the question of whether there are alternative models in which wages can fall. The aim of this paper is to present simple but general models to address this issue.

This paper considers models in which there are an arbitrary number of types of labor, and an arbitrary number of goods that may be used for consumption or capital or both, and arbitrary forms of new technology, seeking necessary and sufficient conditions for when wages may rise or fall.

In our benchmark model we assume that labor is the only fixed factor, that the interest rate is unaffected by new technology, that there are constant returns to scale and perfect competition, and that we are comparing economies with different levels of technology in steady state (an approach also taken in Acemoglu and Autor 2011 and Acemoglu and Restrepo 2018).

In the benchmark model, our first result is that at least one type of worker must be made better-off by new technology. A corollary is that models with only one type of labor must have the feature that real wages rise with new technology. This leaves open the possibility that, if there are many types of labor, workers as a group lose.

Our second main result is that new technology must cause the average wage of workers to rise if the price of capital goods falls relative to consumption goods, a condition that seems satisfied in the data. This leaves open the possibility that there might be very large rises in inequality but we also show that if the supply of labor of different types is perfectly elastic, then all workers must gain.

Taken together these results are more optimistic about the impact of new technology on workers than many current discussions. But they are based on assumptions that may not be satisfied—the paper concludes with a discussion of how alternative models might lead to different conclusions.

## I. Benchmark Model and Main Results

We denote the supply of the many types of labor in the economy by a (row) vector $L$. For the moment we assume the supply of each type of labor is fixed, but we return to this below. We denote wages by a (column) vector $w$ and assume all workers supply labor inelastically and will work for any nonzero wage.

We assume there are many types of consumption, intermediate, and capital goods. Denote the price vector of consumer and/or intermediate goods as $p$ and the rental price of capital goods as $p^K$.

ASSUMPTION CRS: *The production function has constant returns to scale in every sector.*

Denote the unit cost function for consumption/intermediate goods by the vector $c(w,p,p^K,\theta)$ and for investment goods by $c^i(w,p,p^K,\theta)$ where $\theta$ is the level of technology. This setup allows for the possibility that some goods may be impossible to produce (have an infinite cost) at some technologies.

Improvements in technology are captured by assuming that the cost function must be non-increasing in $\theta$ for all goods (both consumption and investment) at constant wages and prices:

$$(1) \qquad c_\theta \equiv \frac{\partial c(w,p,p^K,\theta)}{\partial \theta} \leq 0, \qquad c^i_\theta \equiv \frac{\partial c^i(w,p,p^K,\theta)}{\partial \theta} \leq 0,$$

with a strict inequality for at least one good. For the analysis to be interesting we also need to assume that, for given wages, improvements in technology reduce the price of at least one good that is demanded by consumers. This does not require technology to affect the cost function for these goods directly, it might be an indirect effect through an impact on the costs of producing intermediate or investment goods that are used in that sector. This rules out the possibility that new technology only affects the production of a set of goods that have no link, direct or indirect, to consumption goods. Such a set of goods will have zero production in equilibrium as they serve no purpose.

We need to make some assumptions about how prices are determined.

ASSUMPTION RK: *There are financial assets paying an interest rate r, unaffected by changes in technology.*

The constant interest rate assumption implies that the supply of capital is perfectly elastic in the long run: this could be derived from an underlying model of consumer choice when, in a static steady state, the interest rate would be the rate of time preference, but we do not go into the details here. We also assume that capital goods depreciate at a constant rate $\delta$. Then, a conventional no-arbitrage argument implies that the relationship between the cost of capital and the price of investment goods is $p^K = (r+\delta)p^i$, where $p^i$ is the price of investment goods.

About the nature of markets, we assume the following.

ASSUMPTION PC: *Output and input markets are perfectly competitive.*

PC implies that prices equal unit costs so that we have

$$p = c\big(w,p,(r+\delta)p^i,\theta\big); \tag{2}$$

$$p^i = c^i\big(w,p,(r+\delta)p^i,\theta\big). \tag{3}$$

Finally, we make the following assumption, largely for tractability.

ASSUMPTION HOM: *Consumers' preferences are homothetic so there is a unique consumer price index*, *denoted by* $e(p)$.

## II. Results

In what follows we simply compare steady states with constant levels of technology, asking whether wages are higher or lower in economies with more advanced technology. This approach allows us to be as general as possible about the way in which technology affects production opportunities. But there is a cost—we do not model the transition from one steady state to another, nor do we model an economy in which technology is changing over time. Economic models of growth typically make quite restrictive assumptions about how new technology affects productive opportunities, often to have a model that is analytically tractable and displays balanced growth (Uzawa 1961, Acemoglu 2009, Grossman et al. 2017).

The first result of this paper is the following (proved in the online Appendix).

RESULT 1: *Improvements in technology must raise the real wage of at least one type of worker.*

The intuition for this is that, conditional on prices and wages, costs are weakly decreasing in technology. This means that, conditional on wages, all prices must be weakly decreasing in technology. This means that no price increase can be larger than the largest wage increase. For this group of workers, real wages must therefore be rising.

A corollary of Result 1 is that in models with only one type of labor, new technology of any form must raise real wages for all workers.

Result 1 says that at least one group of workers must gain from new technology but leaves open the possibility that almost all workers lose. However the next result provides a sufficient condition for the average wage to rise.

RESULT 2: *Improvements in technology raise the average real wage of workers if the price index of investment goods does not increase relative to the price index of consumption goods.*

This result is the main result of the paper so the proof is in the main text. Given assumption HOM the expenditure function for workers can be written as $e(p)\,u^w$ where $e(p)$ is the price index and $u^w$ is the (column) vector of utilities for each type of worker. In equilibrium, total expenditure must equal total income for each type of worker which gives us

$$w = e(p) u^w. \tag{4}$$

The total utility of workers will be $Lu^w$, which can be interpreted as (total) real wages. Using (4) and taking logs we have that:

$$\log Lu^w = \log Lw - \log e(p). \tag{5}$$

Now consider a change $d\theta$ in technology. From (5) we have that

$$\frac{Ldu^w}{Lu^w} = \frac{Ldw}{Lw} - \frac{e_p(p)dp}{e(p)} = \frac{Ldw}{Lw} - \frac{X^w dp}{Lu^w e(p)} = \frac{1}{Lw}[Ldw - X^w dp], \tag{6}$$

where $X^w$ is the vector of consumption demands by workers, and we have used Shephard's Lemma to substitute out for $e_p$.

Given the assumption that existing capital all depreciates at a rate $\delta$, to maintain capital stocks of $K$ in a steady state requires investment of $I = \delta K$. Capital owners have total income per period of $(r+\delta) p^i K$, but have to spend $\delta p^i K$ on maintaining their capital holdings, so have total consumption expenditure of $rp^i K$.

Since the prices of consumption goods equal their unit costs, the change in prices from a change $d\theta$ in technology can be written as

$$\begin{aligned} dp &= c_w dw + c_p dp + c_k dp^k + c_\theta d\theta \\ &= c_w dw + c_p dp + (r+\delta) c_k dp^i + c_\theta d\theta, \end{aligned} \tag{7}$$

and the change in the price of investment goods can be written as

$$\begin{aligned} dp^i &= c_w^i dw + c_p^i dp + c_k^i dp^k + c_\theta^i d\theta \\ &= c_w^i dw + c_p^i dp + (r+\delta) c_k^i dp^i + c_\theta^i d\theta. \end{aligned} \tag{8}$$

From Shephard's Lemma, total demands for intermediate goods, $X^d$ can be written as

$$X^d = Xc_p + Ic_p^i = Xc_p + \delta K c_p^i. \tag{9}$$

There is also an equivalent equation for the demand for capital goods:

$$K^d = Xc_k + Ic_k^i = Xc_k + \delta K c_k^i. \tag{10}$$

And total demands for labor can be written as

$$L^d = Xc_w + Ic_w^i = Xc_w + \delta K c_w^i. \tag{11}$$

In equilibrium, we must have the complementary slackness condition $(L - L^d)w = 0$. This implies that if wages for a particular type of labor are positive, then demand for that type of labor must equal supply. But if the wages for a particular type of labor are zero, then it is possible that demand is less than supply and there is some unemployment of that type of labor. Here we assume that $L = L^d$ for all types of labor as this makes the algebra simpler. But we discuss the other case in the online Appendix—it does not alter the result.

Now pre-multiply (7) by $X$, the total vector of consumption goods (some of which are used as intermediate goods) and (8) by $I$ and sum them to have

$$\begin{aligned} Xdp + Idp^i = {} & Xc_w dw + Ic_w^i dw + Xc_p dp + Ic_p^i dp + (r+\delta)Xc_k dp^i \\ & + I(r+\delta)\, c_k^i dp^i + (Xc_\theta + Ic_\theta^i)d\theta. \end{aligned} \tag{12}$$

Using (9)–(11) this can be written as

$$[X - X^d]dp + Idp^i = Ldw + (r+\delta)Kdp^i + [Xc_\theta + Ic_\theta^i]d\theta. \tag{13}$$

Now $X - X^d = X^w + X^k$ where $X^w$ is consumption of workers and $X^k$ is consumption of capitalists, and $I = \delta K$ in steady state in which case we have

$$[Ldw - X^w dp] + [rKdp^i - X^k dp] = -[Xc_\theta + Ic_\theta^i]d\theta > 0. \tag{14}$$

The first term in square brackets is, from (6), the change in the total utility of workers. The second term in square brackets is related to the change in the total utility of capitalists. The sum of these terms must be positive saying that the gains from new technology must flow either to workers or capitalists. But this does not say that workers must get some share of the gains. But (14) can be written as

$$\begin{aligned} Ldu^w &= [Ldw - X^w dp] = [X^k dp - rKdp^i] - [Xc_\theta + Ic_\theta^i]d\theta \\ &= \left[(p \circ X^k)\frac{dp}{p} - r(p^i \circ K)\frac{dp^i}{p^i}\right] - [Xc_\theta + Ic_\theta^i]d\theta, \end{aligned} \tag{15}$$

where $\circ$ denotes a Hadamard product and $dp/p$ is the vector of proportional changes in prices. Equation (15) can then be written as

$$\begin{aligned} Ldu^w &= pX^k\left[\frac{(p \circ X^k)\frac{dp}{p}}{pX^k} - \frac{(p^i \circ K)\frac{dp^i}{p^i}}{p^i K}\right] - [Xc_\theta + Ic_\theta^i]d\theta \\ &= pX^k\left[\frac{d\tilde{p}}{\tilde{p}} - \frac{d\tilde{p}^i}{\tilde{p}^i}\right] - [Xc_\theta + Ic_\theta^i]d\theta, \end{aligned} \tag{16}$$

where the first line uses the fact that from the capitalists' budget constraint $pX^k = rp^iK$ and $\tilde{p}$ is the consumer price index and $\tilde{p}^i$ the investment goods price index. The term in the difference in inflation rates is positive if investment goods prices fall faster than consumer goods prices (e.g., because consumer goods involve more labor-intensive services), proving the result.

The importance of the price of investment goods relative to consumption goods can be understood through a simple model. In clarifying the role of the assumptions it is useful to reduce the number of goods and labor to one but to assume the relative price of investment goods is affected by technology, $p^i(\theta)$ (what Greenwood, Hercowitz, and Krusell 1997 term investment-specific technical change). Represent the gross output of the economy through the use of a production function:

$$Y = F(L, X, K, \theta), \tag{17}$$

where labor is, $L$, intermediate inputs, $X$, and capital, $K$, and the state of technology $\theta$. Normalize the price of the consumption good to 1 and denote the wage paid to labor by $w$. With a constant interest rate the cost of capital will be $p^i(\theta)(r+\delta)$.

With constant returns to scale, the total payment to inputs exhausts total output. So total payments to labor can be written as

$$wL = F(L, X, K, \theta) - X - p^i(\theta)(r+\delta)K, \tag{18}$$

i.e., gross output net of the intermediate goods used and the payments to the owners of capital. Differentiating (18) with respect to new technology leads to

$$\begin{aligned} L\frac{\partial w}{\partial \theta} &= \frac{\partial F}{\partial \theta} + \left[\frac{\partial F}{\partial X} - 1\right]\frac{\partial X}{\partial \theta} + \left[\frac{\partial F}{\partial K} - p^i(\theta)(r+\delta)\right]\frac{\partial K}{\partial \theta} - (r+\delta)K\frac{\partial p^i}{\partial \theta} \\ &= \frac{\partial F}{\partial \theta} - (r+\delta)K\frac{\partial p^i}{\partial \theta}, \end{aligned} \tag{19}$$

where the second equality follows because the terms involving $X$ and $K$ cancel under the assumption that these inputs are paid their marginal product. The first term in the second line is positive as is the second term if the relative price of investment goods is falling. Result 2 simply shows the same is true with many goods and types of labor.[1]

The intuition for Result 2 is that new technology allows more output to be produced than before. This extra output might go to labor or the owners of capital. But if the impact of new technology is to reduce the price of investment goods relative to consumption goods, then the return to existing capital must fall, causing a rise in the overall return to labor. And any additional capital must be paid its marginal product so its return cannot be at the expense of labor. Result 2 does not imply that the labor share of national income rises (Karabarbounis and Neiman 2013) because the stock of capital might increase enough to more than offset the fall in relative investment goods prices.

[1] Casual inspection of (19) might lead one to think that if the relative price of investment goods rises enough, wages could fall even with one type of labor which would contradict Result 1. But if there is no technical regress in producing capital goods there is an upper bound on the increase in the price of investment goods which is that $\frac{\partial \ln p^i}{\partial \theta} \leq \frac{\partial \ln w}{\partial \theta}$, in which case (19) implies real wages must rise.

It is obviously important to consider whether the condition that investment good prices fall relative to consumption goods is likely to be satisfied in practice. Most data suggests that it is (Krusell et al. 2000, Jones 2016, IMF 2017). But one implication is that it is possible to come up with an example in which new technology raises the relative price of capital goods and the average wage of workers falls—this is done in the online Appendix.

Results 1 and 2 do not say anything about whether all or most workers benefit—it is possible that the majority of workers lose or that there will be no demand for some types of workers even if their wages fell to zero. So Results 1 and 2 do not say that new technology will not have serious consequences for inequality in labor income. But there are policies that could ensure all workers gain. With the assumption that the number of different types of workers is fixed, one can simply tax the winners and distribute to the losers without affecting any production decisions. Note that one can achieve this by taxing only labor—one does not need to tax "robots" as has been suggested by, among others, Bill Gates (though see Guerreiro, Rebelo, and Teles 2017 for a different argument supportive of taxing robots). This process of redistribution may be politically difficult—especially if the winners and losers are in different countries—and one should not be complacent about the ability of political processes to restrain rises in inequality. But it is important to understand that there is a simple policy to ensure that all gain.

## III. Choice of Occupation

The models used so far have assumed that the supply of different types of workers is fixed. In the long run, that is not a plausible assumption—think of types of labor as occupations and that workers can choose their occupation at the start of their careers. It is plausible that the numbers of workers choosing different careers depends on wages, the costs of training for different occupations, and how pleasant or unpleasant is the nature of the work. One prominent case is that the labor supply to different occupations is perfectly elastic, which means that relative wages are fixed—occupations which require longer periods in education or are more unpleasant have to be compensated by higher wages.

The perfect elasticity model may seem extreme but is not a bad approximation to the data—over time there have been huge changes in the level of employment in different occupations but more modest changes in relative wages.

RESULT 3: *If labor of different types is in perfectly elastic supply, then workers of all types must gain from technological progress.*

The intuition for this result is that perfectly elastic labor supply between occupations means that wage differentials are fixed, so that all wages must go up or down together, reducing the model effectively to one with only one type of labor. And a corollary of Result 1 is that if there is only one type of labor, then new technology of any form must raise real wages for all workers. The benchmark model does not model the costs of the acquisition of human capital but, with perfectly elastic supply of labor to occupations, utility must be equalized across them and if there is an "entry-level" occupation without training costs then utility net of training costs must also rise as the wage in the entry-level occupation will be rising as wages rise.

## IV. The Role of the Assumptions of the Benchmark Model

As indicated in the introduction, these models are only as good as their assumptions. Here we indicate how the results can change if the assumptions are violated. It is easiest to consider relaxing assumptions in the context of the one type of labor, one good model with the price of investment relative to consumption goods fixed at 1. Results 1 and 2 then imply that workers must gain from new technology if the assumptions of constant returns to scale, a constant interest rate, and perfect competition are satisfied. Now consider how one might try to overturn this result by varying these assumptions.

### A. *Decreasing Returns to Scale*

A very simple example of a decreasing returns to scale production function where the wage can fall is $(L + \theta X)^{\alpha}$ for $\alpha < 1$. Decreasing returns to scale is often thought to result from an "omitted" fixed factor. So this result could be interpreted to say that while new technology increases the returns to fixed factors as a whole, labor is not the only fixed factor. Although it is a common and plausible assumption that labor is currently the main fixed factor, it is possible that some other fixed factor comes to be important, e.g., if robots required some rare earth in their manufacture. In that case it is possible that the benefits from new technology go to the owners of that scarce factor and not to labor. But this is a different argument from most accounts of the impact of new technology. The models of Hanson (2001) and Susskind (2017), in which workers are harmed by new technology, rely on assuming decreasing returns or that labor is not the only fixed factor.

### B. *Imperfect Competition*

If there is imperfect competition, then prices will be a markup on marginal costs. Markups do not necessarily cause the results outlined above to fail. For example, Result 1 will still apply if one inserts markups (possibly different for different goods), as long as markups are constant. But it is conceivable that technical change causes markups to rise for some goods in which case it is possible for wages to fall. The simplest way to see this is to note that $\frac{\partial p^i(\theta)}{\partial \theta}$ in (19) could be very large and positive if technology causes investment goods industries to become less competitive and the markup to rise. There are concerns about rising markups (Autor et al. 2017; De Loecker and Eeckhout 2017), but, even if relevant, it is less about the direct impact of technology and more about the way technology affects market competition. One could also get falling real wages if there was imperfect competition in the labor market and technology increased the market power of employers.

Imperfect competition also allows for increasing returns to scale in production. The online Appendix presents a simple model where each individual firm has increasing returns to scale and some market power, but there is free entry of firms into industries (i.e., a model of monopolistic competition). It shows this is isomorphic to the models already considered if the fixed and variable costs of firms use inputs in the same proportions. So our main results would apply in this case but one could conceivably get different results if fixed and variable costs use different types of inputs.

### C. *Rising Interest Rate*

The online Appendix shows that if new technology causes the interest rate to rise then this causes a rise in the return to capital and possible falls in real wages. In most standard economic models the interest rate is a function of the underlying growth rate (zero in our steady state) and the rate of time preference. There is no particular reason why new technology would affect the rate of time preference so the mechanism for why interest rates might rise are not clear to us but we outline it as a hypothetical possibility.

New technology might increase the growth rate of the economy increasing the interest rate. This would tend to reduce the real wage but the higher growth rate may cause wages to rise at a faster rate ultimately leading to higher real wages. Our model with its comparison of steady states is silent about what might happen in a dynamic economy. But the current problem facing many advanced economies does not seem to be one of fast productivity growth and high real interest rates.

### D. *Non-Steady States*

Our comparison of steady states allows us to be relatively general about the way that new technology affects production, but does come at the cost that we do not analyze the transition from one steady state to another, and do not analyze an economy in which technology changes over time. This leaves open the possibility that new technology causes real wages to fall along the growth path. However, it is well-known that these analyses are hard—one has to impose more restrictions than we have done to have a tractable model of economic growth. One way in which our comparison of steady states may be limited is in its analysis of a singularity if it becomes possible to produce robots that are identical to (or better than) people. If this is the case, then labor is no longer effectively a fixed factor. In a steady state this is a situation in which wages would fall to zero and prices of all goods would also fall to zero if there is perfect competition. This would be an economy of total abundance because there is no longer a natural limit to the level of production caused by the existence of labor as a fixed factor. But one could not get to the point of total abundance instantaneously, so a model of transition would be needed. Aghion, Jones, and Jones (2017) provide a useful discussion of this case emphasizing the restrictive conditions under which singularities might be relevant.

## V. Conclusion

The possible impact of new technology on workers has attracted a lot of attention. Although there are many specific models which seek to investigate this, the existing literature does not lay out conditions under which new technology can be expected to harm no workers, all workers, or reduce the average wage. This paper has tried to do this using very simple underlying models. One underlying theme is that it is harder than one might think to write down economic models in which workers as a group are harmed by new technology: the reason is that if labor is the only fixed factor and the terms of trade shift in favor of workers as the relative price of investment goods decline, then workers as a whole are likely to gain from new technology. And if the supply of labor to different occupations is perfectly elastic, then all will gain. The threats to wages from new technology may come more from impacts on the competitiveness of markets.

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