OF PENCILS AND COMPUTERS

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I. Introduction

In an influential paper, Alan Krueger (1993) asked "Have Computers Have Changed the Wage Structure?" He further refined this question by focusing on "*the issue of whether employees who use computers at work earn more as a result of applying their computer skills, and whether the premium for using a computer can account for much of the change in the wage structure*." (p. 34, emphasis in the original). Krueger concludes that the answer to the first question is "yes" and that computers can account for between one-third and one-half of the increase in the rate of return to education.

In a paper that appears to be on its way to being equally influential, John DiNardo and Jörn-Steffen Pischke (1997) demonstrate that there is a robust relation between earnings and using other office tools such as pencils as well as with computers. They conclude that the case for workers being paid for applying their computer skills is weak.

In this note, I consider what can and cannot be learned from such exercises. I argue that the combination of 1) a measured premium for computer use, 2) a decline in computer prices and 3) growth in the use of computers creates a reasonable prima facie case that computers could have contributed significantly to changing the wage structure in the United States. Since there is no exogenous source of an increase in pencil use, the finding (DiNardo/Pischke) that there is a "premium to pencil use" in no way undermines the plausibility of the original argument.[1]

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[1] DiNardo and Pischke are careful only to conclude that their work undermines the argument that people are paid directly for computer skills and not to draw overly strong conclusions from their exercise. However, their paper has been widely interpreted more strongly.

However, the argument is limited to plausibility. It is possible to write down sensible models in which there is a measured premium for computer use in which declining computer prices reduce inequality. Moreover, under a wide variety of models, examining the effect of controlling for computer use on the measured return to skill is not informative.

I. Computers vs. Pencils

Let us begin with the following finding from Krueger. In a typical wage equation with controls for many of the other factors that are known to be correlated with wages, computer use and wages are positively correlated. If we use the market-clearing perspective due to Rosen (1974), there are four possible explanations for this correlation:

a. The ability to use computers is a rare skill that is valuable to (at least some) firms and is therefore compensated by the market.

b. The ability to use computers is correlated with a rare skill that is valuable to (at least some) firms and this rare skill is therefore compensated by the market.

c. Using a computer is unpleasant but is valuable to (at least some) firms and is therefore compensated by the market.

d. Using a computer is correlated with unpleasant working conditions that are valuable to (at least some) firms and are therefore compensated by the market.

The distinction between a skill premium as in (a) and (b) or a compensating differential as in (c) and (d) is of no real importance at a formal level. Indeed it is not clear that we can meaningfully distinguish between a setting in which workers are compensated for the cost/disutility of learning computer skills and one in which they are compensated for having those computer skills. In either case, workers for whom the wage differential exceeds the (amortized) cost of learning computer skills will get the skills and those for whom the cost is greater will not. In what follows, I will therefore limit myself to the discussion of a skill premium. The argument holds *mutatis mutandis* for compensating differentials.

The distinction between case (a) where workers are directly compensated for their computer skills and case (b) where computers are complementary with other skills is more important. It is perhaps obvious that computers could change the wage structure if workers with computer skills were compensated for those skills and more educated (or other high-wage) workers were more likely to have acquired computer skills. It is perhaps less obvious that computers can change the wage structure even if no worker is directly compensated for computer skills. This can arise if computer skills raise the productivity of, for example, more educated workers in certain jobs. Depending on the elasticity of demand for educated workers in these jobs, the demand for educated workers could rise and thus increase the wages of all educated workers. If computer skills were sufficiently common among educated workers, there would be no premium for computer skills even though computers had changed the wage structure by increasing the skill premium.

While Krueger and DiNardo/Pischke focus on interpretation (a), as the following discussion shows, interpretation (b) can be used to make a plausible case that increased availability of computers changed the wage structure. This argument is formalized in the next section but can be summarized as follows:

1. **Computers are complementary with rare skills.** Krueger does provide strong evidence, confirmed by subsequent authors, that computers are complementary with observed skills. Since

workers who work with computers are paid a premium, it is also likely that computers are complementary with unmeasured skills.

2. **The price of computers fell.** This point seems to be well documented.

3. **The demand for skills that are complementary with computers should therefore have risen.** If it were established that computers were p-complements with skills, this would simply apply the definition of p-complementarity. However, the evidence in Krueger, DiNardo/Pischke and elsewhere is not really about p-complementarity. Technologies that use computers tend also to use more skilled labor. Somewhat more speculatively, an exogenous increase in the use of computers increases the productivity of skilled labor (q-complementarity). It is plausible, but does not follow logically, that declining computer prices increase the demand for the skill that is complementary with computers.[2]

4. Increased demand for skill, increased its price, thereby increasing inequality. While at first blush, this seems to be a straightforward application of elementary price theory, on closer examination the issue is somewhat more complicated. Skill is embodied in workers. Increased demand for skill may make it more likely that lower skill workers are matched with computers rather than that the most skilled workers will command an even higher premium.

The DiNardo/Pischke finding that individuals who work with a pencil (and other common office

[2]For a discussion of q- and p- complementarity see Hamermesh (1993, chapter 2). In essence, inputs are q-complements if an increase in the quantity of one raises the marginal product of the other. Inputs are p-complements if a fall in the price of one increases the demand for the other. Thus sewing machines and seamstresses are q-complements. Sewing machines make seamstresses more productive. However, they need not be p-complements. A fall in the price of sewing machines might reduce the demand for seamstresses. If the demand for the output produced by seamstresses and sewing machines is inelastic, the increased productivity from greater use of sewing machines could reduce the demand for seamstresses.

tools) are paid a similar premium makes it less likely that the measured premium for using computers is a true premium rather than due to correlation with unmeasured skill. It is implausible that knowledge of how to use a pencil, or more reasonably, functional literacy is sufficiently rare as to command a premium. It is, however, quite plausible that use of pencils is correlated with rare skills -- the ability to use certain kinds of mathematics or to write well.[3]

As discussed above, computers can change the wage structure even if no individual is actually compensated for their use. In fact, this issue is largely irrelevant for determining whether the growing availability of computer technology changed the wage structure. Even if there were no measurable premium for using a computer once we control properly for skill, computer technology could have a dramatic impact on the wage structure by increasing the demand for skill.

Pencils obviously have not changed the wage structure. To mimic Krueger's argument it would be necessary to make the case that use of pencils had increased because their price had decreased. Points 2-4 in section I simply do not have a parallel in the case of pencils.

II. A Formal Model

The simplest model in which computers would increase the skill differential is one in which learning to use a computer is costly and workers who have computer skills are compensated for this cost. If educated workers find it easier to learn computer skills, the decline in computer prices will "cause" a rise in the return to education.

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[3] Again, a carefully reading of DiNardo/Pischke reveals that they are much more circumspect than some readers of their paper have been.

The pencils results cast doubt on this simple model. It is difficult to believe that workers who use pencils are being compensated for the cost of learning to use them. However, Krueger's implicit model appears to be more sophisticated than that workers are compensated for the cost of learning computer skills. He notes that computer technology could be a complement or a substitute for skilled workers and suggests that they appear to be complements. Thus, he seems to have in mind a model in which lowering the cost of computers increases the demand for more educated workers.

Suppose that skill and computers are complementary in production and that wages depend on skill level alone and not computer use so that profit is given by

$$B = f(S,C) - w(S) - p(C;2) \qquad f_S>0,\ f_C>0,\ f_{CS}>0,\ p_C>0,\ p_2<0 \qquad (1)$$

where B is profit, S is skill, C is a measure of computer use and p is the price of computing. 2 is a shift factor capturing the cost of computing. The price of output has been normalized to equal 1. Note that this formulation implicitly treats workers of different skill levels as effective labor units and output as constant returns to scale.

Assume further that all markets are competitive so that profit equals zero and thus

$$w(S) = f(S,C) - p(C;2). \qquad (2)$$

Theorem: If $p_{C2}<0$, $w_{S2}>0$.

Proof: Differentiate w with respect to 2 to obtain

$$dw/d2 = (f_C-p_C)(dC/d2) - p_2. \qquad (3)$$

The first term, (f_C-p_C), is 0 by the first-order condition for maximizing profits with respect to C so that

$$dw/d2 = - p_2. \qquad (4)$$

and

$$d^2w/dSd2 = - p_{2C}(dC/dS) > 0 \qquad (5)$$

since $dC/dS>0$ if $f_{CS}>0$.

QED

The theorem says that if workers can be treated as effective labor units, if skill and computers are complementary in production, and if the cost of more powerful computers falls by at least as much as the cost of less powerful computers, then when the price of computers falls, wages of more-skilled workers will rise by more than the wages of less-skilled workers.

In the following example skill and computers are complementary. All workers above a given skill level work with a computer while those below this skill level do not. The cut-off skill level depends on the cost of computers. For any given cost of computers, skill level is a sufficient statistic for the wage. However, if either the functional form of the wage equation is misspecified or information about skill is incomplete, computer use will proxy for skill and enter the wage equation.

<u>Example 1:</u>

Profits are given by

$$B = f(S,C) - w(S) - pC \qquad f_s > 0, \qquad (6)$$

where C is a variable equal to either 1 or 0 depending on whether or not the worker uses a computer, S is skill level, w is the wage which is a function of the skill level and p is the (rental) price of a computer. The price of output is normalized to equal 1. $f(S,1)-f(S,0)$ is increasing in S.

Let S* solve

$$f(S^*,1) - f(S^*,0) = pC. \qquad (7)$$

Then all workers with skill greater than S* work with computers while all those with skill below this level do not. The structure of wages is given by

$$w(S) = f(S,1) - pC \qquad \text{if } S \geq S^*$$
$$w(S) = f(S,0) \qquad \text{if } S < S^*. \tag{8}$$

What is the impact of a decline in the price of computers on the distribution of income and the measured and actual return to working with a computer? Note that the value of S* falls. Denote the new critical value as S**. We can consider the effect of the price decline on three categories of workers -- those for whom $S \geq S^*$ experience a wage increase of dp; those for whom $S^* > S > S^{**}$ experience of a wage increase that is strictly between 0 and dp; finally those for whom $S \leq S^{**}$ experience no wage increase. Thus the reduction in price increases income inequality and the skill premium.

The example captures an important element of reality. While the microcomputer revolution certainly increased the computing power available to individuals who would have used a computer anyway, the most dramatic change is in the number of people working directly with a computer.

In the example, there is no increase in the use of computers among those who would have used one anyway, but the declining price of computers raises the earnings of workers who would have used a computer anyway. In fact, this group experiences the largest wage increase. Thus, the decline in price increases inequality. The effect would be even greater if we allowed the price decrease to increase the computing power used by more skilled workers. It is worth noting in passing that, in the example, in the absence of a measure of skill, the measured return to using a computer may increase or decrease as the price of computers falls.

The theorem and the example serve to bring out both the strength of the argument that falling computer prices are likely to have raised the return to skill and the reasons that the argument might be incorrect. Assuming that skill and computers are, in fact, complementary, they point to two potential sources of failure.

First, treating workers as effective labor units might be a poor approximation. For example, computers could be a substitute rather than a complement for certain types of workers, particularly those engaged in relatively routine white collar tasks (Bresnahan, 1999). To capture this possibility, we must move away from models in which workers are essentially effective labor units and consider the demand for different types of labor. If computers make skilled workers more productive and demand for skilled workers is relatively inelastic, the demand for skilled workers will fall. More realistically, computers may have reduced the demand for workers in low-skill white collar jobs.

Second, price reductions in computing might have been more pronounced at the lower end than at the upper end. For example, if the prices of supercomputers were unchanged, the development of the personal computer would have primarily affected workers who previously made limited or no use of computers. Example 1 captures key elements, although not the richness, of the model outlined in Bresnahan (1999). In the example, the spread of technology is from the most valuable to less valuable applications. The declining price of technology has two effects – to broaden the set of tasks (or in the example, people) to which the technology is applied and to reduce the cost, and thus increase the value, of applications to which it is already applied. The effect of technology on inequality depends on the relative importance of these effects and the segments of the workforce to which the technology is spreading.

Thus, changes in the availability of computer technology can have complex effects on inequality. If the growth of computer use is primarily an extension from high skill to lower skill workers or substitutes for high-skill workers, it might not contribute to growing inequality. Given the period Krueger studied, the first effect is unlikely. Computer use was still quite modest and concentrated among relatively skilled workers, both across occupations and within occupations. In addition, while computers may well have substituted for certain types of workers, these were more likely to have been lower skill white collar workers. Overall, computers appear to be complementary with some types of workers since the number of workers using computers increased.

Thus it is plausible that computers increased inequality. We would like to know the magnitude of this impact. I now turn to this question.

III. Measuring the Impact of Expanded Computer Technology on the Wage Structure

In the final link in his argument, Krueger attempts to measure the impact of computers on the wage structure by comparing two sets of regression estimates. First, he regresses the log wage on education without controls for computer use and finds a significant increase in the estimated return to education. He then adds controls for computer use and computer use interacted with education. He finds that the increase in the estimated return to education is dramatically smaller when controls are added. He concludes that for workers who do not use computer, the increase in the education premium has been much more modest than previously believed.

There are two problems with this argument. The first is that if computers increase the demand for skilled workers, they can raise the wages of all skilled workers relative to unskilled workers, regardless of whether they actually work with a computer. The second is that if something else changes the demand for skilled workers, it may also change the relation between skill and computer use. Controlling for computer use may lead us to attribute part of the change to computers when the entire change is due to some other force.

To clarify these point, in this section, I develop a simple example in which there are two sectors, a skill intensive sector that uses computers and an unskilled labor intensive sector that does not. For simplicity, there are only two skill levels, skilled and unskilled, with some of each type used in each sector.

<u>Baseline Economy:</u>

There are fixed supplies of unskilled (u) with measure 1 and skilled labor (s) with measure .75. Output in each sector is produced accorded to a fixed factor proportion technology.[4] In equilibrium the demand for the two types of labor must equal their supplies:

$$u = 1 = 2q_1 + q_2 \tag{9}$$

$$s = .75 = q_1 + 2q_2 \tag{10}$$

where q is the quantity of output in each sector. All agents in the economy have Cobb-Douglas preferences with exponents equal to .5 so that

$$q_1 = p_2 q_2. \tag{11}$$

where p_1 has been set to 1.

Production in sector 2, the skill intensive sector, requires that the workers in that sector have

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[4]Note that this is inconsistent with the evidence that most skill upgrading in recent years has been within industry (Autor, Katz and Krueger, 1998).

computer skills. Firms can teach computer skills to workers at a cost, c, which is distributed uniform (0, 1).[5] Firms can observe c. In addition, firms in sector 2 must pay k=.1 for a computer for each worker.

To find the equilibrium for the baseline economy, use (9) and (10) to find the level of output in each sector (5/12 in the unskilled intensive sector and 1/6 in the skilled intensive sector) and then (11) to find the price of output in the skilled intensive sector (p_2=2.5). Since the market is competitive, the wage costs plus computer and computer training costs must equal the price:

$$1 = 2w_u + w_s \qquad (12)$$

$$2 = w_u + 2w_s + .3 + c_u + 2c_s \qquad (13)$$

where c_u and c_s refer to the training cost for the unskilled worker and skilled worker in sector 2 who are most costly to train. Since 1/6 of unskilled workers and 4/9 of skilled workers are in sector 2, these costs are 1/6 and 4/9, respectively.

Finally note that the marginal workers will receive the same wage in both sectors. However, workers who are less costly to train will receive a premium equal to what they save the firm in training costs. The average premium for using a computer is 1/12 for unskilled workers and 2/9 for skilled workers.

Consider now what happens if we regress the wage on skill level –

$$w = .30 + .23 \text{ skilled.}$$

If we include computer use (employment in sector 2) and an interaction between computer use

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[5] We could equivalently have workers differ in their productivity using computers.

and skill, we get

w = .285 + .083*computer + .144*skilled + .139*skilled*computer.

It is important to note that the regression with controls for computer use, skilled and their interaction fully captures all of the variation that can be explained without knowledge of the cost of teaching computers skills to each worker. It is therefore, in a sense, the best possible regression equation.

Experiment 1 – Lowering the Price of Computers

Let us repeat the exercise above but lower the cost of computers from k=.1 to k=0. Because of the fixed supplies of the two types of labor and fixed factor coefficients, the number of workers in each sector cannot change. Therefore output does not change, nor does the price of output from sector 2. Given this information, we know that the marginal skilled and unskilled worker do not change and therefore the premiums received by workers in sector 2 do not change. However, demand for skilled labor will rise so that its wage will increase and the wage for unskilled labor will fall.

Estimating the same regressions as for the baseline economy, we get

w = .20 +.53 skilled

and then the equation with controls to get

w =.185 + .083*computer + .444*skilled + .139*skilled*computer.

If we compare the skill premiums without controls, we find that the skill premium rose by .3. This is exactly the amount by which, based on the second regression, the skill premium rose for workers who do not use computers.

Thus although the entire change in the wage structure is due to declining computer prices, the approach used by Krueger would attribute none of the change to this source.

Of course, Krueger does find that computers contributed to the changing wage structure. We must therefore ask whether it is possible for Krueger's approach to attribute to computers a change in the wage structure that is, in fact, due to other factors.

Experiment 2 – Eliminating the Need for Unskilled Labor to Use Computers

Let us now return to the assumption that the cost of computers, k, equals .1. Instead, let us alter the baseline economy by allowing for a technological change such that unskilled workers no longer need to use computers in the unskilled sector.

Since the labor requirements in each sector are unchanged, the allocation of labor and actual output in each sector must remain the same, but the wage of skilled workers must rise relative to unskilled workers to maintain equilibrium. In addition, wages of unskilled workers fall further, on average, because none receives a premium for having a low cost of learning to use a computer.

Re-estimating the wage equations, we have

$$w = .196 + .510 \text{ skilled}$$

and

$$w = .196 + .411^{*}\text{skilled} + .222^{*}\text{computer}^{*}\text{skilled}.$$

Note that the effect of using computers and the effect of using computers if skilled cannot be separately identified.

Using the Krueger comparison of the controlled and uncontrolled regressions, we would conclude the 5% of the change in the premium was due to the decreased use of computers among the unskilled workers when, of course, the entire change in the wage structure reflects this technological change.

I do not want to imply that there are no circumstances under which Krueger's specification is correct. If the specification with computer use, schooling and their interaction is literally the production function, then Krueger's approach will be correct. However, this implies that demand for computer users vs. noncomputer users is perfectly elastic at some relative price, an unrealistic assumption.

IV. Conclusion

Much of the discussion in Krueger and the ensuing critique by DiNardo and Pischke centers on whether the coefficient on computer use in a wage equation reflects a true premium for computer use. In fact, this issue is largely irrelevant for determining whether the growing availability of computer technology changed the wage structure. Even if there were no measurable premium for using a computer once we control properly for skill, computer technology could have a dramatic impact on the wage structure.

The important points in Krueger's original paper are that computer technology appears to be complementary with skill and its use is growing rapidly. Under plausible but certainly not all assumptions, reductions in the cost of computer technology explain the growth of its use which will, in turn, increase the return to skill. These points are, in no way, invalidated by the existence of a correlation between pencils and other office tools and earnings.

The analysis has been much more critical of Krueger's attempt to quantify the impact of growing computer use on the wage structure. Nevertheless, the analysis in the previous section suggests that it is more likely that Krueger underestimates than that he overestimates the impact of computers. The reason is that if one accepts that Krueger has made a plausible case that increased availability of computers raised the demand for skilled labor, this should have increased the relative wage of all skilled workers including those who do not work with computers. As discussed in the previous section, Krueger's approach does not attribute this increase to the impact of computers.

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