DISCUSSION PAPER SERIES

IZA DP No. 792

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June 2003

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IZA Discussion Paper No. 792
June 2003

# ABSTRACT

## What Happens When Agent *T* Gets a Computer? The Labor Market Impact of Cost Efficient Computer Adoption*

This paper offers a model to explain how computer technology has changed the labor market. It demonstrates that wage differentials between computer users and non-users are consistent with the fact that computers are first introduced in high-wage jobs because of cost efficiency. Furthermore, skill upgrading occurs because of a reemphasis on non-routine tasks after computer adoption. The model also reveals that neither differences in computer skills nor complementary skills are needed to explain wage differentials between computer users and non-users, skill upgrading, and the changing organization and intensity of work. Finally, the predicted effects on the wage structure following the diffusion of computers are consistent with the empirical evidence.

JEL Classification: J30, J31, O33

Keywords: wage differentials by skill, computer use and skill

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* We gratefully acknowledge David Autor, Eli Berman, Allard Bruinshoofd, Francesco Caselli, Paul David, Bart Diephuis, Eric Gould, Hans Heijke, Hugo Hollanders, Caroline Hoxby, Larry Katz, Jasper van Loo, Erzo Luttmer, Markus Mobius, Joan Muysken, Mark Sanders, Bruce Weinberg, Thomas Ziesemer, and seminar participants at the Dutch Central Bank, Harvard University, Maastricht University and the University of Oxford for their comments on an earlier version of this paper. This research has been supported by grants from the Netherlands Organization for Scientific Research (NWO).

# 1 Introduction

The adoption of computer technology has substantially changed the workplace. Figures from the October Supplements of the U.S. Current Population Surveys show that computer use at work has increased from 24.3 percent in 1984 to 52.5 percent in 1997. This use is not evenly distributed among workers: in 1997, 74.9 percent of the college graduates used a computer, compared to 38.6 percent of the high-school graduates. In addition, computer users are 15-20 percent better paid than non-users (Krueger, 1993). Furthermore, both firm-specific case studies (Levy and Murnane, 1996, Fernandez, 2001 and Autor, Levy and Murnane, 2002) and economy-wide investigations (see Autor, Katz and Krueger, 1998 and Katz and Autor, 1999 for an overview) report a positive correlation between skill upgrading and the use of computer technology.

The higher wages of computer users and skill upgrading suggest that computer technology is a source of skill-biased technological change. The most common explanation is that on-the-job computer use requires specific skills. Apparently these skills are particularly present among higher educated workers, explaining differences in computer use between relatively educated and uneducated workers and rising wage inequality between high-school and college graduates. Apart from computer skills (Krueger, 1993), other studies emphasize the importance of complementary skills (Levy and Murnane, 1996) leading to skill upgrading and rising wage inequality. However, Bell (1996), using U.K. longitudinal data, argues that there appears to be no relationship between computer skills and wages. Furthermore, DiNardo and Pischke (1996) and (1997) comparing U.S. and German cross-sectional data, Doms, Dunne and Troske (1997) combining U.S. cross-sections and establishment data and Entorf and Kramarz (1997) using French longitudinal data, conclude that the higher wages of computer users are likely to be the result of signaling or unobserved heterogeneity between workers. In addition, Chennells and Van Reenen (1997), Doms, Dunne and Troske (1997), Entorf and Kramarz (1997) and Entorf, Gollac and Kramarz (1999) have shown that workers using computer technology were already better paid before its introduction.[1]

This paper offers a model to explain the above empirical evidence in a unified way. More insight into the impact of computers on the labor market could be gained by an experimental approach in which a computer is made available to a randomly drawn group $T$ of treated workers, while a control group $U$ (untreated people) does not get one. An advantage of this approach is that random assignment excludes selection effects. Because of the small scale of this experiment, market effects due to changes in product prices and wages are negligible. The main problem of such an experiment is that it is not clear what kind of computer facilities have to be used, because its usefulness depends on the tasks to be performed, the configuration of the hardware and software, and information available for use. Furthermore, settings between different jobs vary and it seems to be impossible to guarantee an acceptable experiment. In addition, the possibility to use a computer requires users to recognize its options and the practice that the adoption of computers is preceded by a detailed investigation of the workplace can seldom be simulated.

[1] Chennells and Van Reenen (1997), using U.K. establishment-based data, endogenize technology and find that the wage-technology correlation is mainly driven by the impact of higher wages on computer adoption. Entorf and Kramarz (1997) find that one year of experience with using computers adds about 1 percent to the wages of workers using computers. Entorf, Gollac and Kramarz (1999), matching French workers and their firms, find that the wage effects of computer use are highest after 2 or 3 years, the total returns being about 2 percent. Doms, Dunne and Troske (1997) argue that firms using computers employ more higher educated workers and pay on average higher wages both prior to and after adoption.

As an alternative route develop a theoretical approach and look within a firm and consider two identical agents ($T$ and $U$) who have identical jobs. Dealing with artificial agents rather than with real workers has a number of advantages. First, it enables us to investigate the different effects of the introduction of the computer separately, ruling out unobserved heterogeneity. Secondly, it enables us to compare the impact on two identical workers in a situation where one gets a computer and the other does not. Thirdly, it allows for a comparison of the effects of computer use between two workers that differ only in one specified aspect of their job (see also DiNardo and Pischke, 1997 for a discussion on such experiments).

The results can be summarized as follows. First, wages are an important factor in explaining the introduction of computers because the relative costs for high-wage workers to carry out a task are much higher than for low-wage workers accomplishing the same task. Hence, a firm gains more by letting a high-wage worker carry out this task using a computer. This result is consistent with the evidence that computer users earn higher wages both prior to and after adoption. It also reveals that neither computer skills nor complementary skills are needed to explain wage differentials between computer users and non-users. Secondly, the introduction of computers leads to skill upgrading because of a reemphasis on the non-routine job activities at the expense of routine tasks. This result is consistent with the findings of Autor, Katz and Krueger (1998) for within-industry skill upgrading and the estimation results of Fernandez (2001) for within-firm skill upgrading after the adoption of computer technology. Thirdly, although adoption induces skill upgrading and affects wages, we show that wage differentials are unlikely to increase further when computer use becomes more common in lower skilled jobs. Finally, we derive implications for the firm-wide adoption of computers, the way in which workers cooperate and increasing work intensity consistent with the empirical evidence.

The paper proceeds as follows. Section 2 presents the basic model. Section 3 discusses the effects of the diffusion of computers on the wage structure. Section 4 presents some extensions to the model to show effects of firm-wide adoption, the way people cooperate and work together and work intensity. Section 5 concludes.

# 2 A model of computerization

## 2.1 Basic setting

We consider a market in which we investigate the decision making of one firm concerning agents $T$ and $U$, who are identical and produce the same product. In this market every firm treats the wage ($w$) for every agent with any set of skills ($s$) as given. By the same token, the price for the firm's output $p(q)$ is also given, given the specific characteristics ($q$) of the product. A job consists of several tasks, and the production function of the firm describes the time needed by each agent to perform these tasks. We assume that the skill level of the agent and the product characteristics of the good produced determine the time requirements $d$ to carry out the tasks $j(d_j(s,q))$. For convenience, we assume that a job consists of two tasks. Given these ingredients, the firm chooses product characteristics, a division of tasks, and an agent to maximize profits per unit of production:

$$\max_{s,q} p(q) - w(s) \left(d_1(s,q) + d_2(s,q)\right). \tag{1}$$

From the perspective of the two agents, a similar optimization problem occurs in which s has to be held constant:

$$\max_q p(q) - w(s)\left(d_1(s,q) + d_2(s,q)\right). \tag{2}$$

From the agents' perspective the optimal allocation of time to produce one unit of output leads to $\tau_j(s)$ units of time to complete task $j$. The total time needed to produce one unit of output equals

$$\tau(s) = \tau_1(s) + \tau_2(s). \tag{3}$$

For simplicity, assume that task 1 represents aspects of a job that can be computerized and that task 2 includes activities that cannot be computerized. In addition, suppose that agent $T$ gets a computer to perform task 1 and that agent $U$ continues to work without a computer. This "experiment" implies that agent $T$ has to operate a computer which assists him to perform task 1. Optimization of the production function after computerization leads to $\hat{\tau}_2(s)$ (the time needed for task 2) and $\tau_c(s)$ (the time needed to operate the computer). The optimal allocation of time in the production function might change, since it requires $\tau_c(s)$ to operate the computer instead of carrying out task 1 manually. $\tau_c$ depends on $s$ because carrying out the computerized task requires skills and the time involved to operate the computer might vary with $s$. Computerization might also impact the job aspects included in task 2. If the good produced and the way it is produced remains unchanged, there is no reason why the time required for task 2 should change. However, the complementarity or substitutability between task 1 and task 2, represented by changes in the optimal product characteristics $q$ (which has now changed into a complementarity or substitutability between computer technology and particular human tasks) could be regarded as a channel for changing configurations of jobs. Such a relationship arises once a firm uses the possibilities of a computer to change the characteristics of the product, production process, the division of time between the two tasks, or the organization of work. We therefore allow $\tau_2$ to change as a result of computerization into $\hat{\tau}_2$. In the case where $\hat{\tau}_2 < \tau_2$ ($\hat{\tau}_2 > \tau_2$) computer use by agent $T$ results into less (more) time required to perform task 2.[2] Furthermore, this change might depend on $s$, which could lead $\hat{\tau}_2(s)$ to stress different components of $s$ than $\tau_2(s)$.[3] The time agent $T$ needs to produce one unit of output now equals

$$\tau_T(s) = \tau_c(s) + \hat{\tau}_2(s) \tag{4}$$

whereas the time needed by agent $U$ to produce is still given by equation (3).

Define $\theta^j(s) = -(\partial\tau_j(s)/\partial s)/(\tau_j(s))$ as the time for task $j$ saved by a marginal increase in $s$. We assume $\theta^j(s) \geq 0$ because $s$ affects the time needed to perform this task and an increase in s leads to a higher productivity. Now, task 1 is a routine task if the time saved by $s$ to perform this task is less than the time saved to perform task 2, i.e. $\theta^1(s) < \theta^2(s)$ and a skilled task if the time saved by s to perform this task is more than the time saved to perform task 2, i.e. $\theta^1(s) > \theta^2(s)$. We assume that task 1 is a routine task because computer technology generally takes over routine job activities.[4]

If a firm pays a wage $w(s)$, the costs $k$ per unit of output without a

[2] For convenience, we skip the argument s, except in cases where confusion may arise.

[3] Garicano and Rossi-Hansberg (2002) derive that workers specialize in different tasks after computerization. In addition, they perform more management tasks on their own. Autor, Levy and Murnane (2001) show that the work bundled into the non-computerized task becomes more important. In a previous version of this paper, Borghans and Ter Weel (2001) explicitly address the effects of changing product quality and optimal product quality when computers are adopted.

[4] As a counter example in which task 1 is a skilled task, we might think of a chess player. IBM has shown that thinking about algorithms for the next move can be successfully computerized, but at the same time it requires a huge number of skills from the chess player. Yet, moving the chess pieces and intimidating the competitor (task 2) takes the real Garry Kasparov. However, these cases are rare to the extent that we may assume that for the labor market as a whole the effects of cases in which task 1 is a routine task will prevail. See Borghans and Ter Weel (2001) for a more elaborate discussion of this assumption.

computer equal

$$k_{nc} = w(\tau_1 + \tau_2) \tag{5}$$

and with a computer these costs equal

$$k_c = (w + c)(\tau_c + \hat{\tau}_2), \tag{6}$$

where $c$ reflects the costs of computer use.[5] The total costs the employer has to incur when agent $T$ uses a computer are higher than the costs of not using one if $c(\tau_c + \hat{\tau}_2) > w((\tau_1 + \tau_2) - (\tau_c + \hat{\tau}_2))$. This threshold to adopt a computer depends on wage costs relative to computer costs and the time changes in production if the computer is adopted. An assumption for this relationship to hold is that the costs of the computer are related to the time needed to produce one unit of output. This assumption reflects an essential characteristic of the way in which computers are currently used in the workplace, because the part of the working time the computer is actually used depends mainly on the time the employee needs to fulfil the computerized task.[6]

## 2.2 When are computers adopted?

The decision to adopt a computer is based on a break-even point at which the firm's profits are the same for agent $T$, who uses a computer, and agent $U$, who does not use a computer. The break-even point or threshold $b$, at which $c(\tau_c + \hat{\tau}_2) = w((\tau_1 + \tau_2) - (\tau_c + \hat{\tau}_2))$, equals

$$b = w\left(\frac{\tau_1 + \tau_2}{\tau_c + \hat{\tau}_2} - 1\right). \tag{7}$$

[5] These costs can be thought of as maintenance, depreciation and operating costs, but also as costs of new software applications, hardware and technical assistance.

[6] Implicitly we also assume that c has to be paid for the entire duration of the working time, which means that there should be one computer for each employee. This implies that the computer stands idle when the worker is performing task 2.

The break-even wage depends on the wage $w$ and a function of the specific tasks and the skills.[7] If $b > c$, a computer is profitable because the actual costs of the computerization are below the break-even costs. Allowing for some randomness in the costs of computer use, a higher $b$ yields a higher probability of computer use, i.e. $P(\text{computer}) = P(b > c)$. This model has a very simple (but strong) prediction: if $b > c$, the firm will adopt a computer, and if $b < c$, the firm will not adopt.[8]

In equation (7), $1 - (\tau_c + \hat{\tau}_2)/(\tau_1 + \tau_2)$ represents the time gain of using a computer. This term depends on the specific character of the tasks to be performed, but also on the agent's skill level. The time gain reflects the development of new and more efficient applications, software and hardware. With respect to $s$ we obtain that if agent $T$ becomes more efficient in performing both tasks 1 and 2 (i.e., $\tau_c$ and $\hat{\tau}_2$ are relatively low compared to $\tau_1$ and $\tau_2$), he benefits more from computer use than a less efficient worker. In this setting, the relationship of $(\tau_c + \hat{\tau}_2)/(\tau_1 + \tau_2)$ with $s$ can be seen as the skill bias of the adoption of a new technology, because agent $T$'s skills might either be related to the performance of the computerized task ($\tau_c$) or to the other task ($\hat{\tau}_2$). This might provide skilled workers with an advantage to use a computer over unskilled workers. However, workers with high skills to carry out task 2 do not have a higher probability to use computers, if it leaves the ratio $\tau_2/\hat{\tau}_2$ unaffected. Furthermore, even very large differences in

[7] If the computer is only needed for some fraction of the job ($\lambda$), the expression for the break-even point becomes $b = [(w(\tau_1 + \tau_2))/(\tau_c + \lambda\hat{\tau}_2)][1 - (\tau_c + \hat{\tau}_2)/(\tau_1 + \tau_2)]$. The gain from using the computer only for some time further increases the benefits of introducing a computer. The use of the computer in this case can be seen as a situation in which more than one employee makes use of one single computer.

[8] This way of modelling technology adoption is consistent with the approaches of David (1969) and Davies (1979) who also argue that the costs of new technologies are important determinants of its adoption and diffusion. Other approaches predicting the adoption and diffusion of general purpose technologies are also consistent with our model because computer use is pervasive in a wide range of sectors in ways that change their modes of production (e.g., Bresnahan and Trajtenberg, 1995).

computer skills might have only a very moderate impact on computerization if the time needed for task 1 is low compared to the time needed for task 2.

Equation (7) also reveals that the threshold to adopt a computer is lower ($b$ is higher) when the wage costs are higher. This result implies that, given a worker's skill level, differences in wages trigger computer adoption at different points in time for different wage levels, which is consistent with the findings of Doms, Dunne and Troske (1997), who observe that firms paying higher wages are more likely to adopt computers, and the findings of Chennells and Van Reenen (1997), Entorf and Kramarz (1997) and Entorf, Gollac and Kramarz (1999) that high-wage workers have a higher probability to use computer technology than low-wage workers. It is also consistent with the observation that workers adopting computers earn higher wages than non-users prior to adoption but does not address this to unobserved heterogeneity (DiNardo and Pischke, 1997 and Entorf and Kramarz, 1997), computer skills (Krueger, 1993) or other skill advantages of higher educated workers (Levy and Murnane, 1996). Furthermore, the results are consistent with the finding of a relatively low net productivity effect from computer use because it depends on the relative time gain in production and the inclusion of the costs of adopting a computer into the model (Entorf and Kramarz, 1997). Finally, this finding is consistent with the arguments put forward by Bresnahan (1999) that not only skilled jobs are well-suited to computer use but that also jobs at the lower spectrum of the labor market include tasks which can be computerized. The fact that these jobs have not been computerized yet could be explained by the fact that the wages of the workers occupying those jobs are currently not high enough to merit a profitable adoption of computer technology.

## 2.3 Skill upgrading

Skill requirements are the result of the firm's profit maximization. Since a change in the skill requirements affects the productivity in both tasks, changes in the required skills before computerization were not profitable for skill $s$ if

$$\frac{\partial \Pi}{\partial s} = \frac{\partial (p(q) - w(s)(d_1(s,q) + d_2(s,q)))}{\partial s} = 0. \quad (8)$$

The reason for this is that if a firm hires a more-skilled worker in a particular job, its productivity $(1/(\tau_1+\tau_2))$ increases but its wage costs $(w)$ also increase. This tradeoff between higher skills and higher wages gives the firm's optimal skill choice:

$$\frac{\partial w(s)/\partial s}{w} = \frac{\tau_1}{\tau_1 + \tau_2}\theta^1 + \frac{\tau_2}{\tau_1 + \tau_2}\theta^2. \quad (9)$$

After agent $T$ has adopted a computer this changes into

$$\frac{\partial w(s)/\partial s}{w} = \frac{\tau_c}{\tau_c + \hat{\tau}_2}\theta^c + \frac{\hat{\tau}_2}{\tau_c + \hat{\tau}_2}\hat{\theta}^2. \quad (10)$$

To equilibrate the equation, the firm changes its skill demand after computerization. Equation (10) reveals three factors determining the optimal skill level: (i) an increase in the marginal wage costs of skills $((\partial w/\partial s)/w)$ leads to a decrease in demanded skill requirements;[9] (ii) an increase in the advantage of skill $i$ in performing task $j$ (an increase in $\theta^c$ and/or $\hat{\theta}^2$ compared to $\theta^1$ and $\theta^2$) leads to an increase in demanded skill requirements; and (iii) a change in the relative weights of the two tasks in the production process $(\tau_c/(\tau_c + \hat{\tau}_2)$ and $\hat{\tau}_2/(\tau_c + \hat{\tau}_2))$ leads to an increase (decrease) in skill demand in the case of a shift towards a skilled (routine) task.[10]

[9] This can be seen from the second-order condition. Since equation (10) reflects a maximum, the second-order condition for skill $s$ is equal to $[\partial((\tau_c/(\tau_c + \hat{\tau}_2))\theta^c + (\hat{\tau}_2/(\tau_c + \hat{\tau}_2))\hat{\theta}^2)]/[\partial s] < [\partial(\partial w(s)/\partial s]/w)/[\partial s]$. This means that if $s$ becomes more expensive, employers will diminish their skill demands.

[10] Because the relationship between skill and productivity generally differs between both tasks, each task would have different skill requirements if carried out by separate workers.

Keeping the wage structure constant, the condition in equation (10) changes in three different ways after computerization. First, if task 1 becomes a more skilled task, the firm demands a higher skilled worker because of the importance of the skills to effectively operate the computer. Second, the performance of task 2 might demand a more skilled worker because skilled workers gain more time than unskilled workers after the introduction of the computer. Finally, even if the influence of $s$ on both tasks is kept constant, the weight attached to both tasks might change upon the introduction of the computer. In other words, if task 1 is a routine task, skill requirements increase because the computer puts more weight on the performance of task 2. An implication of this latter result is that for all jobs in which the computerized task is a routine task, the introduction of a computer increases skill requirements, even if the effect of skills on both tasks separately is kept constant.

This latter finding provides a novel insight because it implies that even if working with a computer fails to increase the comparative advantage of skilled workers in each task as such, skill requirements might nevertheless be raised. The particular skills that become more important are not necessarily related to operating a computer or to certain tasks that increase productivity due to the adoption of a computer, but might be skills already used before computerization. This observation also offers an explanation for the difficulties encountered in the search for a direct link between technological change and increased demand for particular skills because it is likely

Skill requirements for the routine task would be lower than skill requirements for the skilled task. Since we assume that both tasks cannot be separated, this implies that the actual skill level is a compromise between the skill levels that are optimal for these tasks separately. The skill level resulting from this compromise depends on the time needed for each task. A change in the relative time required for each task affects the weighting of these effects and therefore influences the recruitment decision. See Section 4.2 for a discussion in terms of the model.

that each job that becomes subject to computerization includes other skills that become emphasized in the performance of non-computerized job activities. This results is also consistent with the findings of Levy and Murnane (1996), Fernandez (2001) and Autor, Levy and Murnane (2002) that the time needed to perform non-routine activities rises relative to routine activities after adoption. It is also consistent with upgrading taking place within computer intensive sectors (Autor, Katz and Krueger, 1998).

# 3 The diffusion of computers

To explain whether the adoption of computers and the observed skill upgrading are the result of a bias in the embodiment skills or whether wage costs are likely to explain computer use we address the effects of the diffusion of computers according to both arguments.

Let us start by analyzing the skill argument. According to equation (7), differences in the probability of computer use can be explained by differences in $(\tau_c + \hat{\tau}_2)/(\tau_1 + \tau_2)$. If so, this factor is decreasing in skills as shown in the top panel of Figure 1. If $c \rightarrow 0$, the adoption of a computer is beneficial starting from a skill level of $x$, i.e. when $(\tau_c+\hat{\tau}_2)/(\tau_1+\tau_2) = 1$. Since the unit of measurement is one expressed in time units, $c$ is divided by the wage to be comparable in different situations. In addition, we assume that computer costs are proportional to the productivity of a worker and add a constant factor to the productivity line to represent total costs. The figure shows that when computer costs are high, the break-even decision is at point $z$. With a relatively low $c$, this break-even point is at point $y$.

The bottom panel of Figure 1 shows changes in profits for the firm per unit of time worked when $c$ is either relatively high or low. This panel shows that the firm's profits are increasing in the skill level of its workforce. It also shows that if $c$ drops, the introduction of computers among lower skilled workers further increases the wages of higher skilled workers because their skills become an increasingly scarce factor.

Insert Figure 1 over here

These patterns are different if computer adoption is explained by the level of wages relative to computer costs. In this case the productivity gain for computer use is constant in terms of time units. Since $c$ is equal per unit of time, it is decreasing in wages, explaining computer use restricted to wages of at least $z$ if computer costs are high and at least $y$ if they are low in Figure 2. There are two differences compared to the situation in Figure 1. First, there is no longer a saturation point $x$ beyond which workers will never use a computer, even if $c \rightarrow 0$. Secondly, the bottom panel of Figure 2 shows that the profits of using a computer converge to a constant rate and that the major increases in profits are for the new computer users. For workers already using a computer, the profits reach a maximum at the point at which computer costs are negligible compared to wages. Within the group of computer users, changes in relative wage differentials are comparatively small and disappear if $c = 0$.

Insert Figure 2 over here

Figure 2 tells the most likely story. First, Entorf, Gollac and Kramarz (1999) have estimated the returns to computer use to peak after 2 or 3 years of computer use, the total returns being around 2 percent. This is consistent with the wage effects drawn in Figure 2, but inconsistent with the ever increasing wages of skilled computer users in Figure 1. Secondly, many relatively unskilled workers currently use computers and do not seem to experience problems in using computers because the technology is becoming more user friendly and is adapting to specific needs (e.g., Borghans and Ter Weel, 2003 for an empirical assessment). Also older workers reach similar productivity effects from using computers (e.g., Borghans and Ter Weel, 2002, Weinberg, 2002 and Friedberg, 2003). Thirdly, wage inequality between computer users and non-users is not increasing at an increasing pace in recent periods, which would be necessary for the story in Figure 1 to hold. Finally, computers are a general purpose technology. In our model a general purpose technology is a technology for which the ratio $(\tau_c + \hat{\tau}_2)/(\tau_1 + \tau_2)$ is of similar size (and larger than 1) in all occupations. In that case wage costs relative to computer costs are the main determinant of computer use explaining high-wage workers using computers first and more often by the fact that the benefits outweigh the costs. If the costs fall, low-wage workers also adopt computers.

# 4 Extensions

## 4.1 Firm effects

We assumed that firms decide upon computer technology investments for each worker separately. In practice it seems to be impossible to introduce computers at the workplace of the firm's high-wage workers, leaving low-wage workers unaffected. Our model can be extended to deal with the firm's decision upon adopting computer technology for its entire workforce. To do so, the additional profits from computerization changes into

$$\left(\sum_i w_i + cNf(N)\right)\left(\sum_i \tau_c + \sum_i \hat{\tau}_2\right) - \sum_i w_i \left(\sum_i \tau_1 + \sum_i \tau_2\right). \tag{11}$$

In this equation total wage costs rather than individual wage costs matter; total time spent on both tasks matters and computer costs per worker become lower if the number of employees increases. The function $f$ describes the ratio between the actual costs per worker and the costs per worker in a one-worker firm. Hence, $f(1) = 1$ and since the costs per worker decrease in $N$, $f'(N) < 0$. In a similar fashion, the break-even costs $b$ for computer use per worker now equal

$$b = \frac{1}{f(N)} \frac{\frac{1}{N}\sum_i w\left(\sum_i \tau_1 + \sum_i \tau_2\right) + q}{\sum_i \tau_c + \sum_i \hat{\tau}_2}\left(1 - \frac{\sum_i \tau_c + \sum_i \hat{\tau}_2}{\sum_i \tau_1 + \sum_i \tau_2}\right). \tag{12}$$

Three properties of the break-even decision have changed compared to equation (7). First, the break-even point depends on the level of average wages in the firm rather than on the level of an individual's wage, which is consistent with the evidence from Doms, Dunne and Troske (1997) that firms paying on average higher wages have a higher probability to adopt computers. Secondly, the break-even point depends on the average time spend on a task rather than individual time. So workers who spend only a relatively small amount of time on task 1 might also get a computer (e.g., CEO's and managers). Thirdly, the break-even point is increasing in firm size $N$. Hence, larger firms more easily introduce computers than smaller firms, which is consistent with the evidence presented by Barras (1990) for the financial and business service sectors.

## 4.2 Working together and organizational change

Computers also affect the way in which workers cooperate and work together. Consider a situation in which task 1 is carried out by an unskilled worker, while task 2 is carried out by a skilled worker. This is efficient if the time needed to instruct the unskilled worker to perform task 1 is recovered by the lower wage costs needed to carry out task 1:

$$\frac{\tau_1 - \tau_{instruct}}{\tau_1^{unskilled}} > \frac{w_{unskilled}}{w}. \tag{13}$$

Splitting the two tasks into different jobs is profitable if (i) the wage differential between both workers is large, (ii) instruction time is short, (iii) unskilled workers are relatively good at performing task 1 and (iv) task 1 is a relatively time consuming task.

The introduction of a computer changes the time requirements. If $\tau_c^{skilled} < \tau_c^{unskilled}$ it might be beneficial to undo the separation of tasks into two distinct jobs. However, if there is no skill bias in performing task 1, the fact that the time needed to operate a computer falls might lead to an integration of both tasks again. Computerization might therefore reduce cooperation between workers of different skill levels.[11]

Kremer and Maskin (1997), Acemoglu (1999) and Garicano and Rossi-Hansberg (2002) argue that there is not only a tendency towards a reduction in cooperation between skilled and unskilled workers, but at the same time an increase in cooperation between workers of equal skill level. In our approach, such changes depend on the way in which team work influences the time requirements for certain activities and of the job in general. For example, a weekly meeting ($\tau_{meet}$) in which workers discuss their experiences on their performance of task 2 might save an amount $\tau_{team}$. This is only profitable if

$$1 + \frac{\tau_{meet}}{h} < \frac{\tau_1 + \tau_2}{\tau_1 + \tau_2 - \tau_{team}}. \tag{14}$$

[11]Note that this reintegration process is more likely to occur if the wage differential between skilled and unskilled workers is smaller. Another observation is that if this integration of routine tasks into a skilled job takes place, this reduces the tendency to increase the skill requirements within the job.

The right-hand side of equation (14) increases if task 1 takes less time because of computer use. In this setting, team working becomes profitable when the work becomes more concentrated on task 2, which is consistent with Kremer and Maskin's (1997) and Garicano and Rossi-Hansberg's (2002) approaches of diverging production processes among skilled and unskilled workers, and Acemoglu's (1999) findings of a changing composition of jobs within firms.

### 4.3 Work intensity

The concentration of work on skilled tasks might not only affect the way in which workers cooperate, but also the intensity of their work. Computer use is often associated with work intensification, with the effects of using a computer screen and the increased amount of information that has to be processed being put forward as explanations (e.g., Green and McIntosh, 2001). However, Lantz (1998) shows that workers who spend some time on a computer to email and to use the Internet suffer less from a higher work intensity. According to our model, the introduction of the computer increases work intensity, because it generally increases the time spent on skilled tasks and reduces the time spent on routine tasks. The relatively more time spent on task 2 offers an explanation for the fact that work intensity increases and that computerization of the routine part of the job leads to some offsetting phenomenon captured by sending an email or browsing the Internet.

## 5 Conclusion

Computers have brought about a dramatic change at the workplace. Many have focused on the adoption of computers as a determinant of skill-biased technological change because computer adoption seems to go with increased skill upgrading and rising wage inequality. In this paper we provide a model to show what happens to the job, skill demand, and the organization and intensity of work upon the adoption of computer technology at the workplace by carrying out an experiment using agents $T$ and $U$.

We show that the cross-section result of a computer wage premium of 15-20 percent is not the result of the allocation of higher educated workers to the most complex jobs or some spurious correlations or unobserved skills. Our model reveals that it is more likely to be profitable for a firm to give a high-wage worker a computer because the efficiency gain is relatively larger than for a relatively low-wage worker. Neither computer skills nor complementary skills are necessary to understand why computers are used by high-wage workers; our argument runs through the cost of adoption. These results are consistent with studies based on longitudinal and panel data which typically find that computers are introduced among high-wage workers first, but only lead to very modest wage increases afterwards. Although agent $T$ adopts the computer, the net wage benefits seem to be modest because he also has to pay for using the computer. If the time saved or shifted between tasks is too small or if his wage is too low, adoption will not (yet) occur.

The observation that wages explain the patterns of diffusion and wage differentials between computer users and non-users does not imply that computers have not led to skill upgrading. Our model demonstrates that employers seem to upgrade their workforce because computerization enables firms to use high-skilled workers more effectively as a result of the diminishing importance of routine tasks. The changing way in which workers can be employed also leads to a better understanding of changes in work organization and work intensity. So agent $T$'s job will require more effort and skills to be fulfilled and a reemphasis on skilled tasks as a result of a shift in time in favor of non-routine job activities.

Finally, one might ask whether the model presented in this paper is specific to the adoption and diffusion of computer technology or that the diffusion of any general purpose technology can be explained by our approach. We think that there are two main reasons why this model does not hold for the diffusion of general purpose technologies in general, such as for example electricity. First, the adoption of computer technology is a decision that can be taken at the individual level, which sets it apart from the adoption of other main technologies that are by their nature adopted among large groups in society at the same time. Secondly, although through market forces computer technology leads to changes in production processes and products that are produced, most of the applications of computer technology can be used to support a worker with the tasks he performed before computerization. The tasks a worker has to perform within a particular job remain mainly unchanged, only the time requirements for tasks taken over by the computer are reduced. This may lead, as we have shown, to a different optimal division of time within the job and induce changes in labor demand, but the job does not disappear. The discriminating feature of most other general purpose technologies is that they lead to a whole new production process making redundant entire jobs or industries and create new jobs and tasks. Hence, while most general purpose technologies substitute existing production processes, computer technology generally supports the worker without essentially changing the tasks (see also David, 1990 for a comparison of the adoption and diffusion of the dynamo compared to the computer).

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# Figure 1

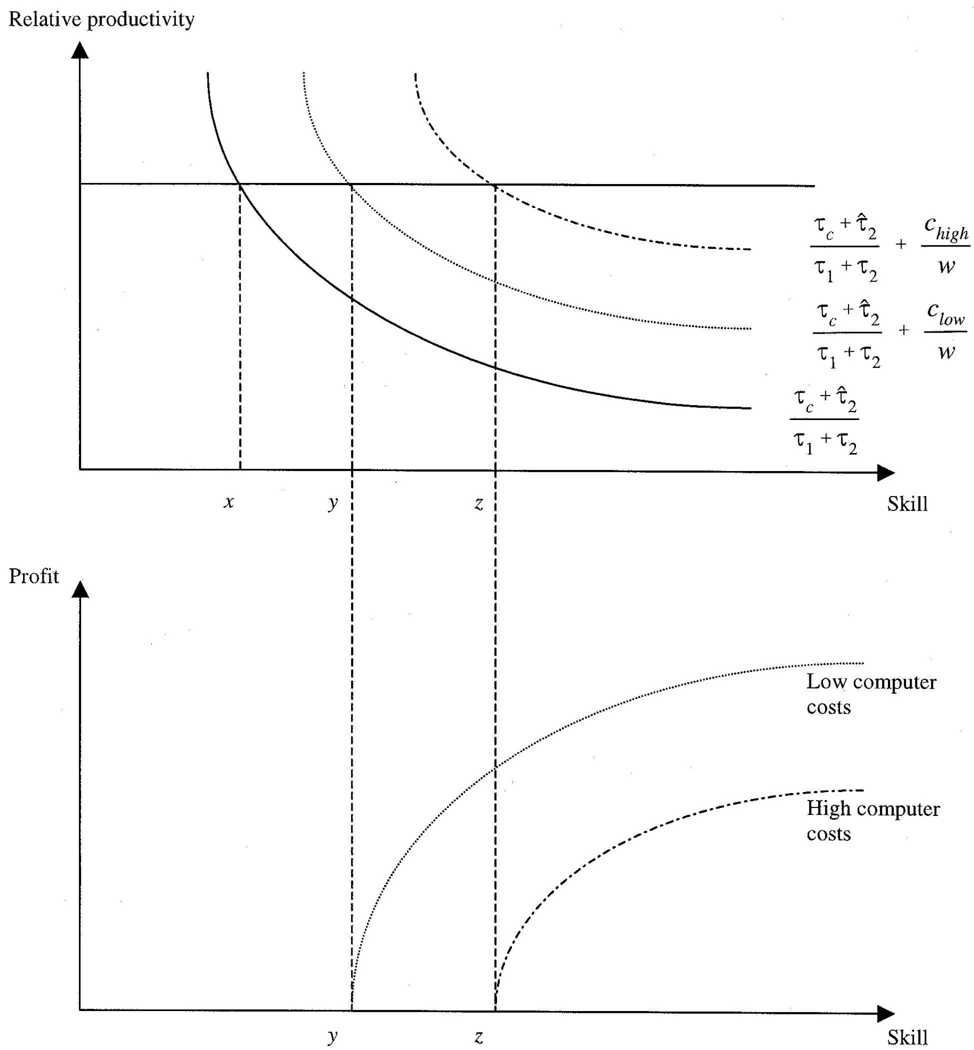
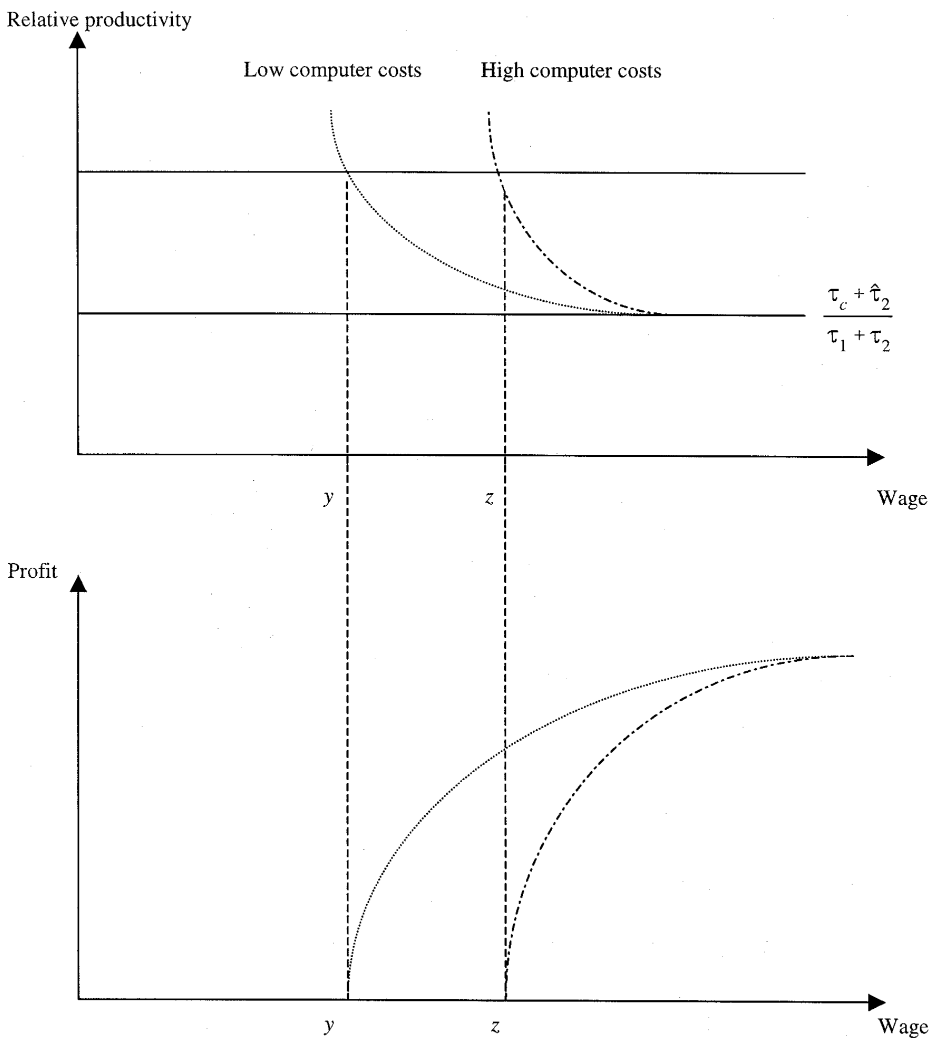

Relative productivity
$\frac{\tau_c + \hat{\tau}_2}{\tau_1 + \tau_2} + \frac{c_{high}}{w}$
$\frac{\tau_c + \hat{\tau}_2}{\tau_1 + \tau_2} + \frac{c_{low}}{w}$
$\frac{\tau_c + \hat{\tau}_2}{\tau_1 + \tau_2}$
x
y
z
Skill
Profit
Low computer costs
High computer costs
y
z
Skill

**Figure 2**


Relative productivity
Low computer costs
High computer costs
$\frac{\tau_c + \hat{\tau}_2}{\tau_1 + \tau_2}$
y
z
Wage
Profit
y
z
Wage

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