The Diffusion of Computers and the Distribution of Wages[*]

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Abstract

This paper offers a theoretical model of the adoption and diffusion of computers at work to analyze between-group and within-group wage inequality, inspired by the empirical observation that the composition of the group of workers using a computer changes over time and that the timing of the rise in between-group and within-group wage inequality is different. The model conjectures that initially only the most productive workers adopt computers, because they can save more on their wage costs. This leads to within-group wage inequality because computer adopters become more efficient. With falling costs of computerization, only when the number of skilled computer users becomes large or when the unskilled workers start to adopt computers, between-group wage inequality increases because the additional supply of efficiency units of unskilled workers depresses the unskilled wages. The occurrence of wage inequality is caused by the additional supply of efficiency units of labor and productivity gains from using computers and not by assuming that skilled workers gain more in terms of productivity from using a computer than unskilled workers. When all workers have adopted computers, between-group and within-group wage inequality disappear unless there are differences in productivity gains between workers. Based on CPS data, it is shown that the predicted pattern of adoption and diffusion is consistent with the observed pattern and the timing of the rise in between-group and within-group wage inequality in the United States in the period 1963-2000.

Keywords: Wage Inequality; Wage Level and Structure; Computerization
JEL Codes: J31, O30

1. Introduction

It has been well documented that wage inequality in the United States has accelerated, upon the emergence of computers in the labor market.[1] Several authors have suggested that the increase in wage inequality has been caused by a complementary relationship between computers and higher skilled labor.[2] In addition, computer use is more concentrated among skilled workers and computer use is associated with higher earnings.[3]

Although much of the econometric evidence indicates that individual computer use leads to wage increases and that particularly higher skilled workers benefit from this, two observations need to be explained. First, computer use among unskilled workers has increased substantially since the early 1980s: In 1997, 42.8 percent of the unskilled workers used a

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[1] It has been argued that the mid-1970s are the watershed in the acceleration of wage inequality. Greenwood's and Yorukoglu's (1997) paper entitled "1974" is indicative in this sense. It starts from the observation that the price of computer equipment fell faster after 1974 than before, which fosters adoption. See also Katz and Murphy (1992), Autor, Katz and Krueger (1998), Krusell, Ohanian, Ríos-Rull and Violante (2000) and Katz and Autor (1999), Katz (2000), Acemoglu (2002) and Aghion (2002) for overviews of this literature.

[2] See for example Krueger (1993) for a seminal paper suggesting that computer users earn 10-15 percent higher wages because of skill advantages, which explains about one half of the widening of the educational wage structure in the period 1984-1989. Levy and Murnane (1996) and Autor, Levy and Murnane (2002) argue that the introduction of computers in a large U.S. bank has induced substitution of unskilled for skilled workers. Berman, Bound and Griliches (1994), Doms, Dunne and Troske (1997), Autor, Katz and Krueger (1998) and Bresnahan, Brynjolfsson and Hitt (2002) observe that higher levels of computerization and investments in computer equipment are associated with higher levels of skill and education in the workforce. Finally, Caselli and Coleman (2001) find a positive correlation between computer adoption and the level of human capital for a large number of countries in the period 1970-1990.

[3] In 1984, 45.2 percent of the skilled and 21.6 percent of the unskilled workers used a computer at work and on average they earned 17.9 and 22.0 percent higher wages than workers from the same skill group who did not use a computer. Here, skilled workers are defined as those with at least a completed college education. Unskilled workers are defined as the remaining ones. These numbers are drawn from the October Supplements of the Current Population Surveys.

computer – an average annual growth rate of 5.4 percent between 1984 and 1997.[4] This change in the composition of the group of computer users raises the question whether the effect of the adoption of computers on wage inequality remains unchanged when its diffusion continues and to what extent wage inequality generated by the diffusion of computers is of a permanent or temporary nature.

Secondly, the timing of the increase in wage inequality needs to be addressed in order to draw a relationship between rising wage inequality and computerization. Figure 1 presents a nine-year moving average of the 90th–10th percentile of the real log annual wage distribution of skilled and unskilled workers from 1963 to 2000 using data from the March Supplements of the Current Population Surveys (CPS) from 1964 to 2001. In the period 1970-2000, wage inequality within the group of skilled workers rises steadily. Within the group of unskilled workers, the period until 1980 is characterized by a fairly stable degree of wage inequality. From 1980 onwards, wage inequality within the group of unskilled workers accelerates. Considering the timing of the adoption of computers, the increase in wage inequality within the group of unskilled workers seems to be broadly consistent with the first unskilled workers adopting computers around 1980. Similarly, the relatively high average annual growth rate of within-group wage inequality for skilled workers since 1970 seems to be consistent with the first appearance of computers in the labor market.

The picture for between-group wage inequality looks quite different. Figure 1 also presents the nine-year moving average of the difference between the mean log annual wages for skilled and unskilled workers from 1963 to 2000. The picture emerging is that between-group wage inequality contracts until the late 1970s. From the early 1980s on it has been

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[4] Computer use at work among skilled workers increased to 76.6 percent in 1997, which is equivalent to a 4.1 percent average annual increase since 1984.

increasing sharply. Comparison of between-group and within-group wage inequality reveals that the timing of the acceleration in between-group wage inequality coincides with the rise in within-group wage inequality for the unskilled and that within-group wage inequality for the skilled workers can only be connected to between-group wage inequality in the 1980s.[5]

Figure 1
Nine-Year Moving Average of Between-Group and Within-Group Wage Inequality in the United States, 1963-2000 (moving average 1963-1971=100)
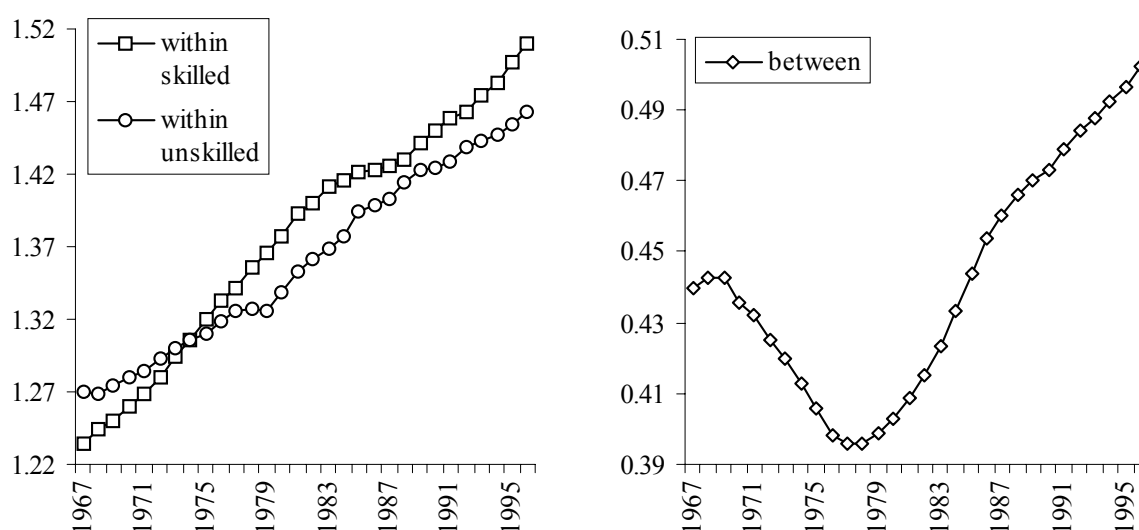
Note: All data are taken from the March CPS and include full-time full-year workers only. Skilled workers are defined as those with at least a college degree. Within-group wage inequality is measured by the 90th–10th real log wage differential within both groups. Between-group wage inequality is defined as the difference between the real log average annual wages of both groups.

This paper develops a theoretical model to analyze how the diffusion of computers shapes between-group and within-group wage inequality. It includes three ingredients: (i) the diffusion of computers is based on cost-benefit considerations weighing the productivity benefits of computer use against the costs of the computer, (ii) fully substitutable productivity

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[5] Autor, Katz and Krueger (1998) also observe that between-group and within-group wage inequality move similarly from the 1980s onwards, but appear to have evolved differently before.

differentials within the groups of skilled and unskilled workers, and (iii) an overlap in the productivity distribution of skilled and unskilled workers, which are substitutable to a limited extent. It is shown that this model explains that (i) between-group and within-group wage inequality increase when computers are adopted even by not assuming that skilled workers gain more in terms of productivity from using a computer than unskilled workers, (ii) wage inequality resulting from computerization is either a permanent or temporary phenomenon – depending on differences between skilled and unskilled workers in the proportional productivity gain from using a computer, (iii) within-group wage inequality for skilled and unskilled workers starts to rise when the first (substantial group of) workers in each group adopt computers, and (iv) between-group wage inequality starts to rise when the group of skilled workers using a computer becomes sufficiently large and particularly when the first (substantial group of) unskilled workers adopt computers.

The predicted pattern of wage inequality for skilled and unskilled workers is the following. When it becomes beneficial for the first group of skilled workers to adopt computers, initially increased efficiency will be offset by the costs of computerization. When the costs continue to fall they gain in terms of wages, which leads to rising within-group wage inequality between adopters and non-adopters. A second effect is that the supply of efficiency units of skilled labor increases, which dampens the relative wages of skilled workers and reduces between-group wage inequality. Given the lower wages of unskilled workers, they adopt computers at a later point in time. When it becomes beneficial for them to adopt, within-group wage inequality increases. The additional units of unskilled labor supply induce between-group wage inequality to rise. When all workers within a group have adopted computers, within-group wage inequality will fall when the costs of the computer fall further. In the hypothetical limit-case where the costs are zero, within-group wage inequality will only

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continue to be larger than prior to computerization if there are differences in the productivity gains from using computers within both groups. When all unskilled workers have adopted computers, between-group wage inequality will decrease because additional efficiency units of unskilled labor are no longer supplied. When the costs of computers continue to fall and go to zero in the limit, between-group wage inequality will be permanently higher than before only if there are productivity differentials between skilled and unskilled workers in using computers. Estimating the model for the United States, using CPS data from 1963-2000, shows that the theory is consistent with the empirical pattern. The increased productivity in efficiency units turns out to be a good explanation for the evolution of the wage ratio. It is observed that (i) the elasticity of substitution between skilled and unskilled workers is between 2 and 3 when accounting for the additional supply of efficiency units of labor and that a considerable fraction of the time trend of relative wages is explained by the model, and (ii) the productivity gain from using computers lies between 15 and 40 percent.

The theoretical model is related to the older literature on the diffusion of new technologies, including the work of David (1969), Stoneman (1976) and Davies (1979), who argue that the costs of new technologies are important determinants of adoption and diffusion.[6] In this paper, (endogenous) wages and productivity gains determine whether computer adoption is beneficial, whereas previous diffusion models treated the determinants of the diffusion process as being exogenous. The analysis in this paper is also related to the more recent studies on technology adoption by Chari and Hopenhayen (1991), Galor and Tsiddon (1997), Caselli (1999) and Weinberg (2001). In these papers, skilled workers have a

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[6] The models predicting the adoption and diffusion of general purpose technologies are also consistent with the theoretical 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 and Helpman and Trajtenberg, 1998).

higher probability to work with new technologies than unskilled workers because new technologies can more productively be operated by skilled workers, but they do not take into account the costs of new technologies in the adoption stage. Violante (2002) assumes noncompetitive labor markets to explain wage inequality among ex ante equal workers in relation to the adoption of new technologies. In his approach, the heterogeneity among workers is not generated by skill differentials but by technological differentials across the machines of different vintages they are matched with. The model presented in this paper is able to distinguish between the moment of computer adoption and the productivity gain resulting from adoption in a fully competitive labor market. In addition, by distinguishing productivity differentials within the groups of skilled and unskilled workers, the theory developed in this paper differs from the above theories and the ones developed by Greenwood and Yorukoglu (1997), Acemoglu (1998) and Kiley (1999) by explaining both between and within-group wage inequality, whereas the other studies mentioned above only analyze wage inequality either within or between groups.[7] Finally, with regard to the distribution of productivity within the groups of skilled and unskilled workers, this paper is related to the approaches of Aghion, Howitt and Violante (1998), Heckman, Lochner and Taber (1998), Galor and Moav (2000) and Gould, Moav and Weinberg (2001). They also use some (ability) distribution to examine within-group inequality. Their distributions are not overlapping, however, whereas our distribution allows for some unskilled workers to have a higher productivity than some skilled workers, which seems to be important from an empirical point of view, because the wages of the skilled worker with the lowest levels of productivity are

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[7] Caroli and García-Peñalosa (2001) also present a model accounting for both between and within-group wage inequality by using differences in wage-setting behavior and wage instability in different stages of technological development. Their model is driven by the assumption that changes in workers' risk aversion induces changes in wages.

lower than the wages of the unskilled worker with the highest levels of productivity. In addition, their mechanism of within-group inequality is determined by differences in abilities or assignment to machines, which leads to the development and transferability of technology-specific skills driving wage inequality, whereas the mechanism of within-group inequality presented here is determined by the costs of computers relative to the wages and the productivity gains from using computers. Finally, the pattern wage inequality resulting from the diffusion of computers presented in this paper is not necessarily caused by the skill-biased nature of computers. Even if computers are assumed to be a skill-neutral technological change, between-group and within-group wage inequality rise in the early stages of computer diffusion. In contrast, the papers discussed above regard technological change to be skill-biased over the second half of the 20th century to generate wage inequality.

The empirical content of the paper for the United States is related to the explanations for wage inequality by Katz and Murphy (1992), Murphy, Riddell and Romer (1998) and Krusell, Ohanian, Ríos-Rull and Violante (2000). The theoretical and empirical observations in this paper offer an additional explanation to rising wage inequality resulting from computerization in that it argues that the additional supply of efficiency units of labor is an important determinant in explaining the rise in between-group wage inequality since the 1980s and accounts for a considerable fraction of the increasing productivity for skilled labor.

The plan of the paper is as follows. Section 2 presents the basic model. Section 3 discusses the temporary and permanent nature of wage inequality resulting from computerization. Section 4 investigates the timing of between and within-group wage inequality. Section 5 empirically addresses to what extent the theoretical model is consistent with the evolution of wages in the United States in the period 1963-2000. Section 6 concludes.

2. The Model

Consider a competitive economy producing a homogeneous good Y that can be used for either consumption or investment. The good is produced by a labor input consisting of S^e units of skilled and U^e units of unskilled workers.

2.1. Basic Structure of the Model

Production

Production occurs according to a constant elasticity of substitution (CES) production function. The output produced equals

$$(1) \qquad Y = (\chi S^\rho + \psi U^\rho)^{1/\rho},$$

where $\rho \le 1$, and the elasticity of substitution between S and U is $\sigma = \frac{1}{1-\rho}$. The supply of skilled and unskilled workers in efficiency units is denoted as S and U, with w_s^{eu} and w_u^{eu} being the corresponding wages in efficiency units. Competitive wages give a standard relative demand equation:

$$(2) \qquad w^{eu} \equiv \frac{w_s^{eu}}{w_u^{eu}} = \left(\frac{\psi U}{\chi S} \right)^{1/\sigma}.$$

For convenience, w_u^{eu} is normalized to 1, so $w_s^{eu} = (\chi S / \psi U)^{1-\rho}$.

Heterogeneity among Workers

Productivity levels are allowed to differ between and within both groups. Productivity differences might be due to unobserved heterogeneity, but might also differ from year to year due to on-the-job learning, aging, sector shifts and other influences, which need not be

specified further.[8] The productivity of skilled and unskilled workers depends on the

parameters $a_i \sim [\underline{\alpha}, \overline{\alpha}]$ with $\overline{\alpha} > \underline{\alpha}$ for skilled worker i and $b_j \sim [\underline{\beta}, \overline{\beta}]$ with

$\overline{\beta} > \underline{\beta}$ for unskilled worker j. The intervals of these parameters are allowed to overlap. The

assumption made is that $\overline{\alpha} > \overline{\beta} > \underline{\alpha} > \underline{\beta}$.

To enable an analytical solution of the model, the distribution of the productivity

parameters for skilled and unskilled workers is assumed to take the following

form: $P^s(a) = \frac{1}{1-\rho} a^{\frac{2\rho-1}{1-\rho}} p^s$ and $P^u(b) = \frac{1}{1-\rho} b^{\frac{2\rho-1}{1-\rho}} p^u$, where $p^s = 1/[(1/\xi)(\overline{\alpha}^\xi - \underline{\alpha}^\xi)]$

and $p^u = 1/[(1/\xi)(\overline{\beta}^\xi - \underline{\beta}^\xi)]$ with $\xi = \sigma - 1$ are obtained from solving the integral for the

distributions of productivity parameters of both types of workers. In the case of a Cobb-

Douglas production function ($\rho = 0$), the assumed distribution is such that the wage bill is

uniformly distributed over the productivity parameters a and b.[9]

Productivity

Each worker has a certain productivity, which depends on his productivity parameter

and whether or not this worker uses a computer. Productivity equals $q_i^s = a_i$ and

$q_j^u = b_j$ without using a computer and $q_i^s = a_i \theta^s$ and $q_j^u = b_j \theta^u$ when using a

computer, where $\theta^s, \theta^u > 1$ is the proportional productivity gain from working with a

computer. Assumptions made are that within both groups the productivity gain from using a

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[8] The model does not require the further specification of this heterogeneity. Because within *S* and *U* workers are perfectly substitutable, any productivity differentials within *S* and *U* is reflected in the wage. Aghion, Howitt and Violante (1998) and Gould, Moav and Weinberg (2001) assume that workers differ in their adaptability to new technologies as a result of random shocks, and Violante (2002) requires that technologies differ in their productivity or quality to generate temporary within-group wage inequality. Caroli and García-Peñalosa (2001) use different attitudes towards risk to generate heterogeneity.

[9] For the CES production function used here, a different elasticity of substitution between skilled and unskilled workers could lead to a slightly different distribution of the productivity parameters.

computer is the same, while between both groups it is allowed to differ,[10] and for all workers there exists some computer application, which makes production more efficient.

Wages

In a competitive labor market, each efficiency unit of labor receives the same return and the wage of a worker equals the productivity parameter multiplied by the return to an efficiency unit of labor. In such a setting, employers are indifferent between employing a worker who uses a computer and one who does not because they pay the same wage for each efficiency unit of labor. This means that both the productivity gain and the costs of the computer are passed on to worker. Hence, wages equal $w_i^s = a_i w_s^{eu}$ and $w_j^u = b_j$ for a worker who does not use a computer and $w_i^s = a_i w_s^{eu} \theta^s - V$ and $w_j^u = b_j \theta^u - V$ for one who does, where V represents the costs of the computer. These costs should be interpreted as the costs of the entire deal, i.e. hardware, software, networks, furniture and technical assistance as well as maintenance, depreciation and replacements costs. Note that V is (implicitly) expressed in terms of w_u^{eu} .[11]

Wages and Computer Adoption

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[10] The alternative assumption would be a complementary relationship between the productivity parameters *a* and *b* and the proportional productivity gain θ. Assuming such a relationship leads to earlier adoption of computers (given the costs of adoption) for workers with a proportional productivity gain $\theta^i > \theta^s$ and $\theta^j > \theta^u$ and to a later adoption of computers for workers experiencing proportional productivity gains smaller than θ^s and θ^u . Such an assumption would, given the costs of computers, lead to a similar of diffusion but to a permanent rise in wage inequality.

[11] We do not explicitly consider differences in the quality of computers, which is rising over time. Considering different vintages of computers in a perfectly competitive market, the most productive workers would be assigned to the most recent vintage. This would lead to a more pronounced level of wage inequality during the time of diffusion but not to different long-run effects.

The decision whether or not to adopt a computer can be written as a trade-off between the increased productivity θ and the costs of the computer V, given the worker's productivity.[12] The break-even productivity for computer adoption for both types of workers then equals

$$(3a) \qquad a_i^{be} = \frac{V}{(\theta^s - 1)w_s^{eu}}$$

and

$$(3b) \qquad b_j^{be} = \frac{V}{(\theta^u - 1)}.$$

Equation (3a) and (3b) show that the break-even productivity at which it becomes beneficial to adopt a computer falls when (i) the costs of the computer V fall, (ii) the productivity gain $\theta - 1$ becomes larger, and (iii) the wage per efficiency unit of labor is higher. Assuming that the costs of the computer are the same for each worker and fall exogenously[13] and continuously, the productivity gain and the wage in terms of efficiency units determine the adoption of the computer.[14] In other words, if the computer is rather expensive, it is only

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[12] Note that the decision to adopt a computer may be different for each individual worker within a firm. This is consistent with the literature investigating inter- and intra-firm technology diffusion. The pattern of diffusion emerging from these studies is that the diffusion of new technology within firms is similar to the diffusion of new technology between firms (e.g., Karshenas and Stoneman, 1993 and Stoneman and Kwon, 1996). Hence, firms are not likely to adopt computers for the entire workforce at once but rather step by step.

[13] The development of computers might also be endogenized by directing a certain fraction of production towards the development of computers. The allocation of labor to a research and development department of the firm or economy then leads to falling costs and higher quality of computers. However, endogenizing the development of computers does not yield additional insight into explaining wage inequality. David and Olsen (1986) develop a diffusion model in which the development of new technology is endogenous to the model. Their conditions for adoption are comparable to the ones derived here.

[14] The costs of the computer might be different for each worker. For example, large firms might have an advantage in maintenance and technical assistance, which leads to lower computer costs per worker. In addition, some workers need a less expensive computer (in

beneficial for the most productive workers to adopt one. Hence, within both groups computer costs relative to wages determine whether or not it is beneficial for a worker to adopt a computer and differences in computer use between skilled and unskilled workers also depend on differences in productivity gains.[15]

Supply of Efficiency Units

The supply of efficiency units of labor consists of two components. First, the sum of all productivity parameters representing total productivity before computerization. Secondly, the productivity gain $\theta - 1$ workers experience from using a computer. The supply of efficiency units of both types of workers then looks as follows:

$$S = S^e \int_{\underline{\alpha}}^{\overline{\alpha}} a_i P^s da_i + S^e \int_{a_i^{be}}^{\overline{\alpha}} (\theta^s - 1) a_i P^s da_i \quad \text{and} \quad U = U^e \int_{\underline{\beta}}^{\overline{\beta}} b_j P^u db_i + U^e \int_{b_j^{be}}^{\overline{\beta}} (\theta^u - 1) b_j P^u db_j.$$

Solving these equations results in the two following expressions for the supply of efficiency units of labor:

(4a)
$$S = S^e P^s \left((\overline{\alpha}^\sigma - \underline{\alpha}^\sigma) + (\theta^s - 1)\left(\overline{\alpha}^\sigma - \left(\frac{V}{(\theta^s - 1)w_s^{eu}} \right)^\sigma \right) \right)$$

and

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terms of the entire deal) than others, which induces earlier adoption, all other things equal. Finally, some workers perform tasks on the basis of ready-made applications, whereas for others with higher wages and higher productivity gains no application is available yet. However, for simplicity the assumption made here is that the costs of the computer are given to the worker and are equal for all workers. Assuming different costs leads to earlier or later adoption, given a worker's wage and productivity gain but do not change the results dramatically.

[15] If, all things being equal, $\theta^s - 1 > \theta^u - 1$, skilled workers gain more in terms of productivity from using a computer, which is equivalent to arguing that they are more efficient in using the computer. Chennells and Van Reenen (1997), Entorf and Kramarz (1997) and Entorf, Gollac and Kramarz (1999) interpret their findings for the United Kingdom and France of high-wage workers using a computer as results in favor of such an explanation.

(4b) $$U = U^e P^u \left((\bar{\beta}^\sigma - \underline{\beta}^\sigma) + (\theta^u - 1)\left(\bar{\beta}^\sigma - \left(\frac{V}{(\theta^u - 1)} \right)^\sigma \right) \right).$$

Equations (4a) and (4b) show that the supply of efficiency units of labor depends positively on the size of the distribution of the productivity parameters α and β, the productivity gain of using a computer θ and the elasticity of substitution between skilled and unskilled workers σ and depends negatively on the costs of the computer *V*.

2.2. Equilibrium Wages

To solve the equilibrium relative wages in efficiency units, equations (4a) and (4b) are substituted into the relative demand equation (2). There are five stages in the diffusion process:[16] (i) no computer use, (ii) the most productive skilled workers use computers, (iii) both types of workers use computers, (iv) all skilled and a fraction of the unskilled workers use computers, and (v) all workers use computers. Table 1 shows the relative wages in efficiency units in each of the five stages. When there is no computer use, the relative wage in efficiency units depends on the supply of efficiency units, the distribution of productivity parameters and the elasticity of substitution between skilled and unskilled labor. In the other four stages, the relative wage in efficiency units also depends on the additional productivity from using a computer, the costs of the computer and the additional units of supply of efficiency units of labor.

INSERT TABLE 1 OVER HERE

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[16] Note that it is possible that certain stages of diffusion will never become effective because of the overlapping productivity parameters between skilled and unskilled workers. For example, given wages, proportional productivity gains and the distribution of productivity parameters, an unskilled worker with productivity $\bar{\beta}$ could reach the break-even point for computer use later than a skilled worker with productivity $\underline{\alpha}$, which would induce computer use among unskilled workers when all skilled workers already have one. This would rule out the third stage.

Table 2 reports the solutions of the equilibrium wages for two skilled workers with productivity parameters a_1 and a_2.[17] The level of the wages in efficiency units and the size of the proportional productivity gain are assumed in such a way that the adoption of computers is assumed to take place in the following order: $\overline{\alpha}$, a_1, $\overline{\beta}$, $\underline{\alpha}$, $\underline{\beta}$ and $\overline{\alpha}$, $\overline{\beta}$, a_2, $\underline{\alpha}$, $\underline{\beta}$. First, consider worker 1 with productivity a_1. When there is no computer use, his wage depends on the relative supply of efficiency units of labor, the distribution of productivity parameters and the elasticity of substitution. At the point in time when $\overline{\alpha} = \dfrac{V}{(\theta^s - 1)w_s^{eu}}$, the first computer is adopted. Once a computer is adopted, the supply of efficiency units increases as a result of the higher productivity when using a computer (e.g., equation (4a)). An increase in the supply of efficiency units of skilled labor has two opposing effects on the relative wage: (i) the rise in the supply depresses the relative wage in efficiency units of all skilled workers and (ii) the productivity of the worker who uses a computer has increased. The equilibrium wage for worker 1 is now lower because the additional supply of efficiency units of skilled labor has depressed the wages of the skilled workers.[18] Once $a_1 = \dfrac{V}{(\theta^s - 1)w_s^{eu}}$, worker 1 adopts a computer. Now, not only does he no longer suffer from other skilled workers using a computer, but he also benefits from the proportional productivity gain θ^s. However, he now has to pay V for adopting the computer. In the third stage, the most productivity unskilled worker adopts a computer and worker 1, and all other skilled workers, gain in terms of relative wages, since the extra supply of unskilled labor will increase the wage of skilled

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[17] The equilibrium wages for other skilled workers with different productivity parameters are straightforward from the results presented in Table 2. In addition, the derivation of the equilibrium wages for unskilled workers is similar to the derivation of the equilibrium wages shown here.

[18] The relative wage of the most productive skilled worker will initially also go down because at the break-even point the positive productivity effect is suppressed by the costs of the computer. This negative wage effect can be very small depending on the parameters of the model and changes into a positive effect on wages after a short period of time.

labor in terms of efficiency units.[19] In the fourth stage, all skilled workers receive the productivity gain from working with a computer, but only a fraction of the unskilled workers use computers. As a consequence, the additional supply of efficiency units of skilled labor comes to a stop. This means that once the spread of computers among skilled workers is complete, they benefit from the increased supply of unskilled labor without experiencing negative wage effects from increases in their own supply. Relative wage growth therefore increases and will be positive for all skilled workers. Ultimately, the least productive unskilled worker also adopts a computer and the supply of efficiency units of both skilled and unskilled labor remains unchanged. With falling costs of computerization, wage differentials will fall since workers with low wages benefit relatively more than high-wage workers. Subsequently, the relative wage equals $(\theta^s/\theta^u)^\rho$ times the relative wage before the computer was introduced.

The relative wages of worker 2 are shown in the second column of Table 2. For worker 2 with productivity a_2 the first two stages show a similar relative wage. However, he only adopts a computer after the most productive unskilled workers have adopted one. This means that in the third stage his wages are already increasing (compared to stage 2) despite the fact that he did not adopt a computer yet. This fosters his adoption of computers because a higher wage induces computer use. When he adopts the computer at $a_2 = \dfrac{V}{(\theta^s - 1)w_s^{eu}}$, his wage increases further. Finally, the last two stages show the same pattern of relative wages as in the case of worker 1.

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[19] A consequence of unskilled workers starting to use computers is that skilled workers who are not using computers also gain from this increased supply of unskilled labor in terms of relative wages. Due to the endogeneity of wages in the model, the rise in skilled wages increases the pace of computer adoption among skilled workers, which at the same time increases skilled labor supply in efficiency units. This effect somewhat dampens the increasing relative wages.

2.3. Wage Inequality and Diffusion over Time

Figure 2 presents the predictions of the model for the wages of workers with productivity levels $\bar{\alpha}$, $\underline{\alpha}$ and $\bar{\beta}$ relative to the least productive worker with productivity $\underline{\beta}$, in terms of the falling costs of adopting computers. The figure shows that when only a fraction of the skilled workers uses a computer, the relative wages for computer adopters fall relative to the least productive unskilled workers, which reflects the net effect of the productivity gain and the additional supply of efficiency units of skilled labor at the first stage of adoption. The negative effect of additional supply is captured by the line for the non-users from the skilled labor force. After the most productive unskilled workers have adopted computers, the wages of both skilled and unskilled workers rise relative to the least productive unskilled worker because the additional supply of efficiency units of unskilled labor dampens the wages of unskilled workers and because the increased productivity of unskilled adopters versus non-adopters. When all skilled workers have adopted computers, wage inequality within the group of skilled workers becomes constant, whereas the wages of skilled workers as a group are still rising relative to the wages of the unskilled workers due to the increase in the supply of efficiency units of unskilled workers adopting computers. Finally, when all workers use computers at work, wage inequality falls. When the costs of computers fall further, both between and within-group wage inequality fall, the extent depending on the different distributions and size of the productivity gains θ.

3. Is Wage Inequality Temporary or Permanent?

If the costs of adopting computers are equal for skilled and unskilled workers and are falling continuously, there are two factors determining computer adoption that shape between-group wage inequality: (i) differences between the proportional productivity gains θ^s and θ^u and (ii) differences in wages (e.g., equations (3a) and (3b)). Comparison of the first and final rows of Table 2 reveals for workers 1 and 2 that at the point of satiation their relative wages only differ from their relative wages before computerization by the factor $(\theta^s/\theta^u)^\rho$. This result implies that when the costs of computers fall sufficiently (i) between-group wage inequality is only a temporary phenomenon if the proportional productivity gains from using a computer are equal $(\theta^s = \theta^u)$, and (ii) differences in wages determining a different adoption point in time also lead to a temporary increase in wage inequality between those who already adopted a computer and those who did not do so yet.

The first result suggests that if $\theta^s > \theta^u$, between-group wage inequality will be permanently higher. The size of this effect depends on the elasticity of substitution and the difference between the proportional productivity gains. Similarly, if $\theta^s < \theta^u$, between-group wage inequality will be permanently lower. Figure 3 graphically presents these three possibilities for worker i with productivity parameter $a_i = \bar{\alpha}$. In all three cases between-group wage inequality first falls, then sharply rises and eventually falls again. If $\theta^s = \theta^u$, between-group wage inequality resulting from computerization is a temporary phenomenon. If $\theta^{s*} > \theta^s$, skilled workers adopt computers earlier (when they are more expensive) because the productivity gain is higher. This induces a faster diffusion process, which first leads to a larger drop in the skilled workers' wages but then to a stronger increase in between-group wage inequality. Eventually, between-group wage inequality falls (at the same point in time as in the situation where $\theta^s = \theta^u$) but has a permanent component depending on the size of ρ and the difference between θ^{s*} and θ^u. If $\theta^{u*} > \theta^u$, unskilled workers adopt computers

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earlier. This first leads to a smaller drop in skilled workers' wages because they gain at an earlier stage from the adoption of computers by unskilled workers. The effect of the additional supply of unskilled workers at an earlier stage fosters the diffusion process among skilled workers and leads to a higher peak in between-group wage inequality. When all unskilled workers have adopted computers (at a higher level of computer costs), between-group wage inequality falls to a level which is lower than the initial level of between-group wage inequality, its size depending on ρ and the difference between θ^{u*} and θ^{u}. A similar exercise for within-group wage inequality reveals similar patterns of the extent and point in time of rising and falling wage inequality.[20]

INSERT FIGURE 3 OVER HERE

The second result suggests that differences in the productivity parameters a and b between workers have no permanent effect on between-group wage inequality. If the proportional productivity gains are similar within both groups, differences in productivity parameters will only influence the length of the diffusion process and the extent of between-group wage inequality in the different phases of computer adoption. If all workers shared the same productivity parameter, they would adopt computers at the same point in time and there would be no within-group wage inequality. This reveals that within-group wage inequality is also a temporary phenomenon, given that the proportional productivity gains are similar within both groups.

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[20] These results crucially depend on the assumption that there are no within-group differences in the proportional productivity gains. If this were the case and workers with a higher productivity parameter gained more from using a computer, between-group wage inequality would be permanent depending on the distribution of productivity parameters. In addition, this would induce within-group wage inequality, the size of which would also depend on the distribution of productivity parameters.

4. The Timing of Wage Inequality

The trends presented in Figure 1 suggest that if one wants to draw causal relationships between the computerization of the labor market and rising wage inequality, it is important to understand and acknowledge the different timing of between-group and within-group wage inequality. Within-group wage inequality for skilled workers has increased since the early 1970s, within-group wage inequality for unskilled workers started to increase in the early 1980s and between-group wage inequality fell until 1980 and increased strongly afterwards.

Within-group wage inequality for worker 1 with productivity a_1 is described by $\frac{a_1}{\underline{\alpha}}\left(\theta^s - \frac{V}{w_s^{eu}(V,\theta^s,\theta^u)a_1}\right)$, which is decreasing in V and increasing in the size of the distribution of productivity parameters and the wage in efficiency units. The extent of within-group wage inequality also depends on the proportional productivity gains θ^s and θ^u : (i) a larger θ^s induces earlier adoption, and (ii) $\theta^s > \theta^u$ ($\theta^s < \theta^u$) leads to a larger (smaller) difference in the timing of adoption. This means that within-group wage inequality is driven by the productivity parameters, the level of wages, the proportional productivity gains and the costs of computers. The different timing of within-group wage inequality resulting from the adoption of computers is then caused by (i) higher productivity parameters and wages for skilled workers, and (ii) higher proportional productivity gains for skilled workers, which makes adoption beneficial at an earlier stage. Figure 4 plots the conjectures of the model for within-group wage inequality for skilled and unskilled workers as a function of the falling costs of computers. The figure shows that the increase in within-group wage inequality for skilled (unskilled) workers started when the first skilled (unskilled) workers adopted computers, which is consistent with the trends presented in Figure 1.

<center>INSERT FIGURE 4 OVER HERE</center>

The behavior of between-group wage inequality is driven by three mechanisms. First,

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when the first skilled worker adopts a computer, his wage equals the break-even wage but one period later his wage will be higher than the break-even wage because of the continuously falling costs of computers and the gains from using the computer. Secondly, when using a computer this worker generates more efficiency units of skilled labor, which decreases the wage in efficiency units (e.g., equation (4a)). Thirdly, when the first unskilled workers adopt computers, all skilled workers benefit in terms of relative wages because the additional supply of efficiency units of unskilled workers depresses their wages. The first and third mechanism induce an increase in between-group wage inequality and the second mechanism depresses between-group wage inequality.

The timing of between-group wage inequality resulting from the computerization of the labor market can then be understood as follows. When the first skilled worker gets a computer, the derivative of his wage with respect to V equals $\dfrac{\partial w_i^{\bar{a}}}{\partial V} = \dfrac{1}{\beta} \left(\dfrac{\theta^s \bar{\alpha}^\sigma}{\theta^s \bar{\alpha}^\sigma - \underline{\alpha}^\sigma} - 1 \right) > 0.$ Wage inequality between the most productive skilled worker and the least productive unskilled worker increases when this derivative is negative, since V is decreasing in time. It is easy to see that the derivative is always positive, so initially the introduction of the computer among skilled workers reduces between-group wage inequality. This means that the increasing supply of efficiency units of skilled labor outweighs the proportional productivity gain at the break-even point. This situation is reversed when $a_i = \bar{\alpha} \left(\dfrac{\theta^s \bar{\alpha}^\sigma - \underline{\alpha}^\sigma}{\theta^s \bar{\alpha}^\sigma} \right)^{1/(\sigma-1)}$ because at this point the derivative of the wage with respect to V equals zero.[21] Once it becomes beneficial for the unskilled workers to start using a computer at work, between-group wage inequality rises because $\dfrac{\psi U^e P^u (\theta^u - 1)^{1-\sigma}}{\chi S^e P^s} > 0.$ This term is always positive, since $\theta^u > 1$. The rise in between-group wage inequality is larger if the proportional productivity gain for

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[21] This result is consistent with the observations of Entorf and Kramarz (1997) for France. They observe that a worker's wage does not jump when he adopts a computer but increases to a higher level rather slowly.

unskilled workers is larger (see also the higher peak for $\theta^{u*} > \theta^u$ in Figure 3) and if

$(\psi U^e P^u)/(\chi S^e P^s)$ is relatively large. This implies that the additional supply of efficiency

units of unskilled workers depresses their wages and induces between-group wage inequality

to rise. Depending on the size of the proportional productivity gain and the distribution of

productivity parameters, this rise can be more or less severe. Hence, between-group wage

inequality starts to increase once unskilled workers adopt computers, which is consistent with

the timing of the increase in between-group wage inequality depicted in Figure 1. Between-

group wage inequality will continue to rise if $-\frac{\partial w_{a_i}}{\partial V} > -\frac{\partial w_{b_i}}{\partial V}$, which will be the case as long

as $a_i > b_i \frac{\theta^u}{\theta^s}$. Given $\theta^u = \theta^s$, between-group wage inequality contracts once the diffusion

of computers is complete.

5. Empirical Analysis

5.1. Data and Construction of Variables

We use the March Demographic Supplements of the CPS from 1964 to 2001 in the

empirical analysis for information about the standard labor-market variables and to construct

labor supply. The October Supplements from 1984, 1989, 1993 and 1997 are used for

information about computer use.

Labor supply is computed for skilled and unskilled workers. Skilled workers are

defined as workers with at least a completed college education and unskilled workers as the

other ones. We use workers employed in the previous year. Full-time workers are weighted

with a factor 1, and part-time workers with the number of hours worked in the preceding

week divided by 40 (the average number of hours worked by the full-time workers). Since the

exact number of weeks worked is not known for several years in the data, full-year workers

are weighted with a factor 1 and part-year workers with a factor .5 (the use of alternative

weights does not change the results in a qualitative sense).

To avoid measurement problems, part-time and part-year workers are not included when constructing the wage variable. Only full-time full-year salaries are used, which provides information on the gross annual wages. Since the dispersion in productivity parameters, reflected by wage differentials within the groups of skilled and unskilled workers, is essential to the model, no correction has been made for demographic factors. To compute real wages we apply the price deflator for personal consumption expenditures from the National Income Product Accounts (NIPA).[22] In terms of the model, wage differentials between skilled and unskilled workers are of interest but within-group wage differentials are also important. The average wages for workers with productivity $\bar{\alpha}$ are defined as the 90th percentile of the wage distribution of skilled workers and the average wages for workers with productivity $\underline{\alpha}$ as the 10th percentile of this wage distribution. Similarly, the average wages for workers with productivity $\bar{\beta}$ are defined as the 90th percentile of the unskilled workers' wage distribution and the average wages for workers with productivity $\underline{\beta}$ as the 10th percentile of the unskilled workers' wage distribution.[23] Since the composition of the U.S. labor force changed in the period 1963-2000, an alternative measure of the wage development has also been used. This alternative measure has been constructed by defining 32 cells for four age groups, four educational groups and controlling for gender. These 32 cells have been weighted such that their sizes are equal to the size in 2000. Based on these weights, average

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[22] The data are taken from the Annual Revision of the NIPA made available by the Bureau of Economic Analysis. 1992 = 100.

[23] In the regression analysis we also test whether the results are sensitive to using the 80th, 70th, 20th and 30th percentiles of both wage distributions.

and percentile wages have been determined.[24] Thus, the composition of the workforce and labor supply within the group of skilled and unskilled workers is equal in all years.[25]

Information about computer use at work is available only for four years in the October Supplements. From these years computer, use has been imputed for 1963-2000. Using full-time full-year workers, computer use among skilled workers equals 45.2 (1984), 62.8 (1989), 70.4 (1993) and 76.6 (1997) percent. Among full-time full-year unskilled workers computer use equals 21.6 percent in 1984, 33.1 percent in 1989, 37.6 percent in 1993 and 42.8 percent in 1997. To calculate computers use in the other years, we have to determine the wages of the marginal worker using a computer. For 1984, the marginal skilled worker is assumed to be at the 54.8^{th} percentile $(100 - 45.2$ percent computer use) of the wage distribution. A similar exercise is performed for the other three years and the unskilled workers. Using these four data points and years, the equation $\ln w = C + \alpha Y + \varepsilon$ is estimated for skilled and unskilled workers, where $\ln w$ is the log of the real annual wage, C is a constant, Y are the years for which computer use is known and ε is an error term with the usual properties. In this setting $\ln w$ can be treated as the break-even wage. The equation for skilled workers is $\ln w = 8.240 - .030\, Y$ and that for unskilled workers is $\ln w = 7.633 - .024\, Y$. To generate computer use, all workers with wages in year Y above the break-even wage are set to use a computer at work. Figure 5 plots this imputed computer use for the 1963-2000 period. The pattern of diffusion is consistent with the often found S-shaped diffusion pattern of new technologies (e.g., David, 1969 for an overview). From Figure 5 it can be read that computer

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[24] The age groups are <29, 30-39, 40-49 and >50, the educational groups are less than highschool, highschool degree, more than highschool but less than a college degree, and a college degree or more.

[25] The use of more than 32 cells does not significantly change the regression results, but leads in some instances to rather low numbers of workers in each cell. The use of less than 32 cells also gives comparable results.

use for the skilled workers has increased rather rapidly since the early 1970s and that computer use for the unskilled workers started to rise around 1980. This prediction for computer use is consistent with the figures presented by Greenwood and Yorukoglu (1997) and Jorgenson (2001) on the falling prices and subsequently rising investments in and use of computers at work.

<center>INSERT FIGURE 5 OVER HERE</center>

5.2. Econometric Specification of the Model

In the theoretical model, we made assumptions about the distribution of productivity parameters to generate an analytical solution. For the estimation we use the actual distribution of productivity parameters. In accordance with the labor demand equation (2) and allowing for a time trend $(e^{\gamma_1 t})$ in the wages, the relative wage in efficiency units equals

$$(5) \qquad\qquad w^{eu} = \left(\frac{\psi U}{\chi S} \right)^{1/\sigma} e^{\gamma_1 t}.$$

The supply of skilled labor S in efficiency units can be determined from

$$S = S^e + S^e (\theta_s - 1) F_s,$$

where F_s denotes the fraction of efficiency units of skilled workers using a computer. This fraction equals

$$(6) \qquad\qquad F_s = \frac{\int\limits_{cu} a_i p^s \mathrm{d}a_i}{\int\limits_{cu} a_i p^s \mathrm{d}a_i + \int\limits_{no} a_i p^s \mathrm{d}a_i},$$

where *cu* is defined as computer users and *no* as non-users. From this equation, a_i is not observed directly, but can be derived from the information about wages according to $a_i = \frac{w_i + V}{\theta_s} = \frac{w_i + (\theta_s - 1) w_{be}^s}{\theta_s}$. In principle, this expression could be substituted in equation (6) and estimated. However, analysis of the data shows that for reasonable values of θ_s , F_s

<center>-24-</center>

is almost constant in θ_s . To avoid estimation problems, F_s is therefore approximated by

(6')
$$F_s = \frac{\int\limits_{cu} w_i p^s \mathrm{d}a_i}{\int\limits_{cu} w_i p^s \mathrm{d}a_i + \int\limits_{no} w_i p^s \mathrm{d}a_i},$$

which can be understood as the wage-bill share of computer users as a fraction of the wage bill of all skilled workers.

For unskilled workers, F_u is approximated in a similar way. The supply of unskilled workers in efficiency units equals $U = U^e + U^e(\theta_u - 1)F_u$. Substituting this expression in equation (5) and (6) provides an econometric equation for the wage ratio of skilled and unskilled labor in efficiency units.

Another problem is that wages in terms of efficiency units are not directly observed. To evaluate the theoretical model, we have estimated: (i) the wage ratio of skilled versus unskilled workers, (ii) the $90^{th} - 10^{th}$ percentile wage differential of skilled workers, and (iii) the $90^{th} - 10^{th}$ percentile wage differential of unskilled workers. The wage of a skilled worker equals

(7)
$$w_i = \gamma_0 w_s^{eu} + \gamma_0(\theta_s - 1)w_s^{eu} C_i^s - V C_i^s,$$

where $C_i^s = 1$ if worker i uses a computer and 0 otherwise. Since $V = (\theta_s - 1)w_{be}$, averaging over all skilled workers leads to

(8)
$$\overline{w}_s = \gamma_0 w_s^{eu} + \gamma_0(\theta_s - 1)w_s^{eu}\overline{C} - (\theta_s - 1)w_{be}\overline{C},$$

where a bar over a variable indicates an average term. Dividing by $\overline{w}_u$, rearranging terms and taking logs gives

(9) $$\ln\left(\frac{\overline{w}_s}{\overline{w}_u}\right) = \ln\left(\gamma_0 w^{eu}\left(\frac{\overline{w}_u + (\theta_u - 1)w_{be}^u \overline{C}_u}{\overline{w}_u}\right) + \gamma_0(\theta_s - 1)w^{eu}\overline{C} - (\theta_s - 1)\frac{w_{be}}{\overline{w}_u}\overline{C}\right).$$

Substituting equation (5) for w^{eu}, this equation can be estimated by non-linear least squares with θ_s, θ_u, γ_0 and γ_1 as the unknown parameters.

Similarly, the 90th–10th percentile wage differential within the group of skilled workers can be written as

$$(10) \qquad w_{90^{th}}^s = \gamma_0 w_s^{eu} + \gamma_0(\theta_s - 1) w_s^{eu} C_{90^{th}}^s - V C_{90^{th}}^s,$$

where $C_{90^{th}}^s$ indicates the years in which the 90th percentile of the wage distribution of skilled workers adopted a computer. According to the imputed computer use data, this is after 1974. Dividing by equation (10) $w_{10^{th}}^s$ yields the equation for estimating within-group wage inequality:

$$(11) \qquad \ln\left(\frac{w_{90^{th}}^s}{w_{10^{th}}^s}\right) = \ln\left(\gamma_0 + \gamma_0(\theta_s - 1) C_{90^{th}}^s - (\theta_s - 1)\frac{w_{be}}{w_{10^{th}}^s} C_{90^{th}}^s\right),$$

which also has to be estimated by non-linear least squares. Similarly, the regression equation for the within-group inequality of unskilled workers is

$$(12) \qquad \ln\left(\frac{w_{90^{th}}^u}{w_{10^{th}}^u}\right) = \ln\left(\gamma_0 + \gamma_0(\theta_u - 1) C_{90^{th}}^u - (\theta_u - 1)\frac{w_{be}}{w_{10^{th}}^u} C_{90^{th}}^u\right).$$

5.3. Basic Estimates

Table 3 reports estimates for 1963-2000 of the log of equation (5), which is similar to the equation used by Katz and Murphy (1992) to estimate for the period 1963-1987. The first column reports estimates not taking into account the additional efficiency units of labor resulting from computerization. In the next four columns, the additional supply of efficiency units are controlled for by including θ^s after 1974 and by including θ^u after 1980.[26] In the

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[26] These are the years in which 10 percent of the population within both groups use computers according to the imputed computer use shown in Figure 5. Including years close to 1974 and 1980 does not substantially change the results. Including thresholds of 5 and 15 percent does

second column, θ^s and θ^u equal 1.2 in the second column, 1.3 in the third column and 1.4 in the fourth column. The last three columns report estimates for $\theta^u = 1.1$ and $\theta^s = 1.2$, 1.3 and 1.4. The rows at the bottom of Table 3 report estimates when weighing the wages and the supply of labor to keep the composition of the labor force constant.

The regression results reported in the first column are comparable to the estimates reported by Katz and Murphy (1992). They obtain an estimate for β of −.71 for a comparable but different definition of skilled and unskilled workers, compared to −.55 here, suggesting an elasticity of substitution between skilled and unskilled workers of 1.82 (−1/β). The use of weighted series does not lead to a significantly different estimate. The annual increase in the demand for skilled labor is about 2.4 percent, which is lower than the 3.3 percent obtained by Katz and Murphy (1992). Adjustment of supply of skilled and unskilled workers by including the additional supply of efficiency units of labor resulting from computer use leads to significantly higher estimates for the elasticity of substitution between skilled and unskilled labor. For the non-weighted series, the elasticity of substitution increases to 2.73 if $\theta^s = \theta^u = 1.4$, with the annual increase in the demand for skilled labor remaining being fairly constant. Similarly, the results are comparable when assuming different proportional productivity gains for skilled and unskilled workers.[27] Because the regression includes only 38 aggregate observations and there is likely to exist serial correlation in the relative wages, these estimates have to be interpreted with care. However, the estimates being higher when including the adjusted labor supply series suggest an increase in wage inequality to explain the pattern of the data. Whereas Katz and Murphy (1992) explain the trend towards lower between-group wage inequality in the 1970s and rising wage inequality since 1980 by a rather

not qualitatively change the results.

[27] Here the elasticities of substitution lie between 2.21 and 2.95.

low rate of substitution between skilled and unskilled workers, these estimates suggest that a significantly higher elasticity of substitution between skilled and unskilled workers is also able to explain the data when the supply is adjusted for the productivity gain experienced by computer users.

INSERT TABLE 3 OVER HERE

5.4. Between-Group Wage Inequality

Table 4 reports the results from estimating equation (9). The first column reports estimates in which the proportional productivity gains are not allowed to differ from one another, i.e. $\theta^s = \theta^u$. In addition, the data used are not weighted for differences in composition. The table reports an estimate for $\theta^s = \theta^u = 1.15$, an elasticity of substitution of 2.52 and a time trend of approximately 1.4 percent a year, which reflects the average annual increase in the demand for skilled labor. These estimates suggest that the proportional productivity gain from computer use is substantial (15 percent) and lies between approximately 5 and 25 percent. This productivity gain can also be interpreted as the costs of the computer relative to the wage of the marginal worker who just adopted a computer. Considering that these are the costs for the entire deal, this estimate seems reasonable. Finally, the relatively low estimate for the time trend compared to the estimate presented in the first column of Table 3 suggests that the model explains about 40 percent of the increased demand for skilled labor.

The second column of Table 4 reports estimates allowing for differences in the productivity gain between skilled and unskilled workers. The point estimate is about 19 percentage points higher for skilled workers compared to unskilled workers $(\theta^s = 1.27$ and $\theta^u = 1.08)$ and also substantially higher for skilled workers than the 15 percent productivity

increase reported in the first column where $\theta^s = \theta^u$. This suggests that skilled workers gain more in terms of productivity than unskilled workers. However, the margins are rather large and it is not possible to statistically discriminate between the coefficients for skilled and unskilled workers. The elasticity of substitution turns out to be relatively high, but given the substantial margins, its precise magnitude is not so clear from this regression. The time trend is .9 percent, which is lower than in the previous estimates.

Overall, these results suggest that including the productivity gains from using computers and the subsequent additional supply of efficiency units of labor is important to explain the developments in between-group wage inequality.[28]

INSERT TABLE 4 OVER HERE

5.5. Within-Group Wage Inequality

Table 5 reports the results of estimating equations (11) and (12) for within-group wage inequality. The estimation is based on an analysis of the $90^{th} - 10^{th}$ percentile of both wage distributions and uses the non-weighted data. The regression equation is set such that for computer use below the 10 percent level, within-group wage inequality is constant. The first column of Table 5 reports an estimate for the proportional productivity gain of $\theta^s = 1.41$ with margins between 1.35 and 1.47. This suggests a productivity gain of around 40 percent from using a computer. The regression results reported in the second column of Table 5 suggest a similar proportional productivity gain for unskilled workers ($\theta^u = 1.41$) although the confidence interval is somewhat wider. In terms of the costs of using a computer, these estimates are rather high (also compared to the estimates for between-group wage inequality). They suggest that the costs of the computer are approximately 40

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[28] When weighing wages and labor supply, the results turn out to be similar.

percent of the wage of the marginal worker who adopts the computer.[29] However, the size of the estimates is consistent with the regression coefficients reported by Bresnahan, Brynjolfsson and Hitt (2002, Table 8). They argue that there are large adjustments costs to the successful use of computers, which are not only due to the installation of computers itself but also to the change in organization structure and other coinventions going along with computerization.[30]

To investigate whether these relatively high estimates are sensitive to the measure of within-group wage inequality, two different definitions also have been tested. First, the 80th–20th percentile of the wage distribution has been used as a measure of wage inequality. Now, $\theta^s = 1.21$ with a lower margin of 1.15 and an upper margin of 1.26 and $\theta^u = 1.28$ with margins of 1.18 and 1.38. Secondly, the 70th–30th percentile of both wage distributions have been investigated. Here, $\theta^s = 1.15 \ (1.10, 1.20)$ and $\theta^u = 1.12 \ (1.00, 1.24)$. These estimates suggest that the proportional productivity gains are lower when within-group wage inequality is allowed to fluctuate after 20 and 30 percent of the workers within each group have adopted computers.

INSERT TABLE 5 OVER HERE

The interpretation of the different estimates for the proportional productivity gains in Tables 4 and 5 can be viewed upon as lower and upper bound productivity gains. The relatively low estimate for the productivity gain reported in Table 4 suggests that the additional supply plays an important role, and the relatively high estimates for the

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[29] Weighing the data to control for compositional changes during 1963-2000 gives estimates of $\theta^s = 1.29$ and $\theta^u = 1.47$.

[30] An alternative interpretation of these estimates for the productivity gain compared to the between-group estimates is to consider different vintages of computers. This would lead to the interpretation that the productivity gain of the latest vintage, compared to not using a computer, equals approximately 40 percent.

productivity gain reported in Table 5 are probably caused by addressing all within-group differences to computerization. When using a more moderate definition of within-group wage inequality, the effects are much more modest, suggesting lower productivity gains more in line with the estimates of between-group wage inequality.

6. Conclusions

This paper offers a theoretical model to explain increasing between-group and within-group wage inequality resulting from the spread of computers since the 1970s. The model conjectures that through the falling costs of computers, its adoption is determined by wages and proportional productivity gains. As a consequence, the composition of the group of workers using computers has changed over time. The diffusion path and the changing composition of computer users determine the extent and timing of between-group and within-group wage inequality resulting from the adoption and diffusion of computers. It has been shown that within-group wage inequality starts to increase once the first workers in each group have adopted computers. Consistent with the numbers depicted in Figure 1, this happened in the early 1970s for skilled and around 1980 for unskilled workers. Between-group wage inequality started to rise when the first unskilled workers adopted computers. The reason for between-group wage inequality to rise is that additional supply of efficiency units of unskilled labor depresses the unskilled workers' wages. The innovative features of the model presented in this paper are twofold. First, the timing of the increase in between-group and within-group wage inequality is explained. Second, we observe that even when skilled workers do not experience a larger productivity gain from using a computer than unskilled workers, the observed rise of between-group and within-group wage inequality can be explained by the model.

An empirical analysis using CPS data suggests that the pattern of between-group and within-group inequality predicted by the theoretical model is consistent with the pattern of wage inequality in the United States in the period 1963-2000. The model explains an additional 40 percent of the rising between-group wage inequality. In addition, it is shown that the relatively low values for the elasticity of substitution between skilled and unskilled workers from the literature are likely to reflect the omission of additional supply of efficiency units. The estimates presented here lie between 2 and 3. The estimates for the proportional productivity gain of using a computer are between 15 and 40 percent.

For the further diffusion of computers through the labor market, the theory predicts falling between-group and within-group wage inequality when the diffusion is complete and when the costs of the computer continue to fall. In the hypothetical situation where the costs of computer adoption are zero, between-group wage inequality resulting from computerization will continue to exist only if the productivity gains experienced is higher for skilled workers than for unskilled workers. Although the confidence intervals are rather large, the estimates suggest a slightly higher productivity gain for skilled workers, which would generate a permanent increase in wage inequality due to computerization. Within-group wage inequality resulting from computerization will also disappear if the productivity gains are equal within the groups of skilled and unskilled workers. If these gains are different, workers gaining more in terms of productivity will receive higher wages.

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Table 1
Relative Wages in Efficiency Units in Each of the Five Stages

Stage	Relative wages in efficiency units
No computer use	$$\frac{w_s^{eu}}{w_u^{eu}} = \left(\frac{\psi\, U^e P^u (\overline{\beta}^\sigma - \underline{\beta}^\sigma)}{\chi\, S^e P^s (\overline{\alpha}^\sigma - \underline{\alpha}^\sigma)} \right)^{1/\sigma}$$
The most productive skilled workers use computers	$$\frac{w_s^{eu}}{w_u^{eu}} = \left(\frac{\psi\, U^e P^u (\overline{\beta}^\sigma - \underline{\beta}^\sigma)}{\chi\, S^e P^s (\theta^s \overline{\alpha}^\sigma - \underline{\alpha}^\sigma)} + \frac{(\theta^s - 1)^{1-\sigma} V^\sigma}{\theta^s \overline{\alpha}^\sigma - \underline{\alpha}^\sigma} \right)^{1/\sigma}$$
Both types of workers use computers	$$\frac{w_s^{eu}}{w_u^{eu}} = \left(\frac{\psi\, U^e P^u (\theta^u \overline{\beta}^\sigma - \underline{\beta}^\sigma) + (\chi\, S^e P^s (\theta^s - 1)^{1-\sigma} - \psi\, U^e P^u (\theta^u - 1)^{1-\sigma}) V^\sigma}{\chi\, S^e P^s (\theta^s \overline{\alpha}^\sigma - \underline{\alpha}^\sigma)} \right)^{1/\sigma}$$
All skilled and some unskilled workers use computers	$$\frac{w_s^{eu}}{w_u^{eu}} = \left(\frac{\psi\, U^e P^u \left((\theta^u \overline{\beta}^\sigma - \underline{\beta}^\sigma) - (\theta^u - 1)^{1-\sigma} V^\sigma \right)}{\chi\, S^e P^s \theta^s (\overline{\alpha}^\sigma - \underline{\alpha}^\sigma)} \right)^{1/\sigma}$$
All workers use computers	$$\frac{w_s^{eu}}{w_u^{eu}} = \left(\frac{\psi\, U^e P^u \theta^u (\overline{\beta}^\sigma - \underline{\beta}^\sigma)}{\chi\, S^e P^s \theta^s (\overline{\alpha}^\sigma - \underline{\alpha}^\sigma)} \right)^{1/\sigma}$$

Table 2
Individual Workers' Wages Before and After Adopting Computers in Different Stages of Diffusion

Stage	Wage for Worker 1 with Productivity Parameter a_1	Wage for Worker 2 with Productivity Parameter a_2
1	$\dfrac{1}{\beta}\left(\dfrac{\psi U^e P^u(\overline{\beta}^\sigma - \underline{\beta}^\sigma)}{\chi S^e P^s(\overline{\alpha}^\sigma - \underline{\alpha}^\sigma)}\right)^{1/\sigma} a_1$	$\dfrac{1}{\beta}\left(\dfrac{\psi U^e P^u(\overline{\beta}^\sigma - \underline{\beta}^\sigma)}{\chi S^e P^s(\overline{\alpha}^\sigma - \underline{\alpha}^\sigma)}\right)^{1/\sigma} a_2$
2a	$\dfrac{1}{\beta}\left(\dfrac{\psi U^e P^u(\overline{\beta}^\sigma - \underline{\beta}^\sigma)}{\chi S^e P^s(\theta^s\overline{\alpha}^\sigma - \underline{\alpha}^\sigma)} + \dfrac{(\theta^s-1)^{1-\sigma}V^\sigma}{\theta^s\overline{\alpha}^\sigma - \underline{\alpha}^\sigma}\right)^{1/\sigma} a_1$	$\dfrac{1}{\beta}\left(\dfrac{\psi U^e P^u(\overline{\beta}^\sigma - \underline{\beta}^\sigma)}{\chi S^e P^s(\theta^s\overline{\alpha}^\sigma - \underline{\alpha}^\sigma)} + \dfrac{(\theta^s-1)^{1-\sigma}V^\sigma}{\theta^s\overline{\alpha}^\sigma - \underline{\alpha}^\sigma}\right)^{1/\sigma} a_2$
2b	$\dfrac{1}{\beta}\left(\dfrac{\psi U^e P^u(\overline{\beta}^\sigma - \underline{\beta}^\sigma)}{\chi S^e P^s(\theta^s\overline{\alpha}^\sigma - \underline{\alpha}^\sigma)} + \dfrac{(\theta^s-1)^{1-\sigma}V^\sigma}{\theta^s\overline{\alpha}^\sigma - \underline{\alpha}^\sigma}\right)^{1/\sigma} a_1\theta^s - V$	$\dfrac{1}{\beta}\left(\dfrac{\psi U^e P^u(\overline{\beta}^\sigma - \underline{\beta}^\sigma)}{\chi S^e P^s(\theta^s\overline{\alpha}^\sigma - \underline{\alpha}^\sigma)} + \dfrac{(\theta^s-1)^{1-\sigma}V^\sigma}{\theta^s\overline{\alpha}^\sigma - \underline{\alpha}^\sigma}\right)^{1/\sigma} a_2$
3a	$\dfrac{1}{\beta}\left(\dfrac{\psi U^e p^u(\theta^u\overline{\beta}^\sigma - \underline{\beta}^\sigma) + (\chi S^e p^s(\theta^s-1)^{1-\sigma} - \psi U^e p^u(\theta^u-1)^{1-\sigma})V^\sigma}{\chi S^e p^s(\theta^s\overline{\alpha}^\sigma - \underline{\alpha}^\sigma)}\right)^{1/\sigma} a_1\theta^s - V$	$\dfrac{1}{\beta}\left(\dfrac{\psi U^e p^u(\theta^u\overline{\beta}^\sigma - \underline{\beta}^\sigma) + (\chi S^e p^s(\theta^s-1)^{1-\sigma} - \psi U^e p^u(\theta^u-1)^{1-\sigma})V^\sigma}{\chi S^e p^s(\theta^s\overline{\alpha}^\sigma - \underline{\alpha}^\sigma)}\right)^{1/\sigma} a_2$
3b	$\dfrac{1}{\beta}\left(\dfrac{\psi U^e p^u(\theta^u\overline{\beta}^\sigma - \underline{\beta}^\sigma) + (\chi S^e p^s(\theta^s-1)^{1-\sigma} - \psi U^e p^u(\theta^u-1)^{1-\sigma})V^\sigma}{\chi S^e p^s(\theta^s\overline{\alpha}^\sigma - \underline{\alpha}^\sigma)}\right)^{1/\sigma} a_1\theta^s - V$	$\dfrac{1}{\beta}\left(\dfrac{\psi U^e p^u(\theta^u\overline{\beta}^\sigma - \underline{\beta}^\sigma) + (\chi S^e p^s(\theta^s-1)^{1-\sigma} - \psi U^e p^u(\theta^u-1)^{1-\sigma})V^\sigma}{\chi S^e p^s(\theta^s\overline{\alpha}^\sigma - \underline{\alpha}^\sigma)}\right)^{1/\sigma} a_2\theta^s - V$
4	$\dfrac{1}{\beta}\left(\dfrac{\psi U^e p^u\left((\theta^u\overline{\beta}^\sigma - \underline{\beta}^\sigma) - (\theta^u-1)^{1-\sigma}\right)V^\sigma}{\chi S^e p^s\theta^s(\overline{\alpha}^\sigma - \underline{\alpha}^\sigma)}\right)^{1/\sigma} a_1\theta^s - V$	$\dfrac{1}{\beta}\left(\dfrac{\psi U^e p^u\left((\theta^u\overline{\beta}^\sigma - \underline{\beta}^\sigma) - (\theta^u-1)^{1-\sigma}\right)V^\sigma}{\chi S^e p^s\theta^s(\overline{\alpha}^\sigma - \underline{\alpha}^\sigma)}\right)^{1/\sigma} a_2\theta^s - V$

5

$$\frac{1}{(\underline{\beta}\theta^u - V)}\left(\frac{\psi U^e p^{\,u}\theta^u(\overline{\beta}^\sigma - \underline{\beta}^\sigma)}{\chi S^{\,e} p^{\,s}\theta^s(\overline{\alpha}^\sigma - \underline{\alpha}^\sigma)}\right)^{1/\sigma} a_1\theta^s \; - \; V$$

$$\frac{1}{(\underline{\beta}\theta^u - V)}\left(\frac{\psi U^e p^{\,u}\theta^u(\overline{\beta}^\sigma - \underline{\beta}^\sigma)}{\chi S^{\,e} p^{\,s}\theta^s(\overline{\alpha}^\sigma - \underline{\alpha}^\sigma)}\right)^{1/\sigma} a_2\theta^s \; - \; V$$

Note: Stage 1: No computer use; Stage 2a: The most productive skilled worker adopts a computer; Stage 2b: Worker 1 adopts a computer; Stage 3a: The most productive unskilled worker adopts a computer; Stage 3b: Worker 2 adopts a computer; Stage 4: All skilled workers have adopted a computer; and Stage 5: All workers have adopted computers.

Table 3

Some Basic Estimates of the Time Trend and the Elasticity of Substitution for Different
Productivity Gains from Using Computers

	$\theta = 1$	$\theta = 1.2$	$\theta = 1.3$	$\theta = 1.4$	$\theta^s = 1.2$ $\theta^u = 1.1$	$\theta^s = 1.3$ $\theta^u = 1.1$	$\theta^s = 1.4$ $\theta^u = 1.1$
β	$-.549$	$-.464$	$-.412$	$-.366$	$-.453$	$-.390$	$-.339$
	(.105)	(.066)	(.056)	(.048)	(.074)	(.067)	(.061)
α	.024	.021	.019	.018	.022	.020	.019
	(.004)	(.003)	(.002)	(.002)	(.003)	(.003)	(.003)
β	$-.531$	$-.536$	$-.493$	$-.448$	$-.550$	$-.513$	$-.472$
	(.179)	(.116)	(.097)	(.083)	(.121)	(.103)	(.089)
α	.028	.028	.027	.025	.030	.030	.030
	(.007)	(.005)	(.004)	(.003)	(.005)	(.005)	(.004)

Note: All data are taken from the 1964-2001 March CPS files. The dependent variable is the log of the ration of the average wages of skilled and unskilled workers. Skilled workers started to use computers in 1974 and unskilled workers in 1980.

Table 4
Estimates for Between-Group Wage Inequality

|	Equal Proportional Productivity Gains				Different Proportional Productivity Gains			
			95% confidence Interval				95% confidence interval	
	Estimate	Standard Error	Lower	Upper	Estimate	Standard Error	Lower	Upper
θ	1.150	.045	1.058	1.242				
θ_s					1.272	.071	1.128	1.416
θ_u					1.079	.058	.961	1.197
σ	2.517	.556	1.388	3.646	4.298	1.837	.560	8.037
γ_1	.014	.004	.005	.022	.009	.004	.000	.017
γ_0	.299	.127	.042	.557	.585	.264	.048	1.121
R^2				.785				.812

Note: All data are taken from the 1964-2001 March CPS files. The dependent variable is the log of the ration of the average wages of skilled and unskilled workers. Computer use is imputed using the October Supplements of the 1984, 1989, 1993 and 1997 CPS files (see the note below Figure 5). The regressions are performed by non-linear least squares.

Table 5
Estimates for Within-Group Wage Inequality

|	Skilled workers				Unskilled workers			
			95% confidence interval				95% confidence interval	
	Estimate	Standard Error	Lower	Upper	Estimate	Standard Error	Lower	Upper
θ_s	1.413	.029	1.354	1.472				
θ_u					1.412	.047	1.317	1.507
γ_0	3.524	.030	3.463	3.584				
R^2				.883				.751

Note: All data are taken from the 1964-2001 March CPS files. The dependent variable is the log of the $90^{th}-10^{th}$ percentile wage differential within both groups. Computer use is imputed using the October Supplements of the 1984, 1989, 1993 and 1997 CPS files (see the note below Figure 5). The regressions are performed by non-linear least squares.
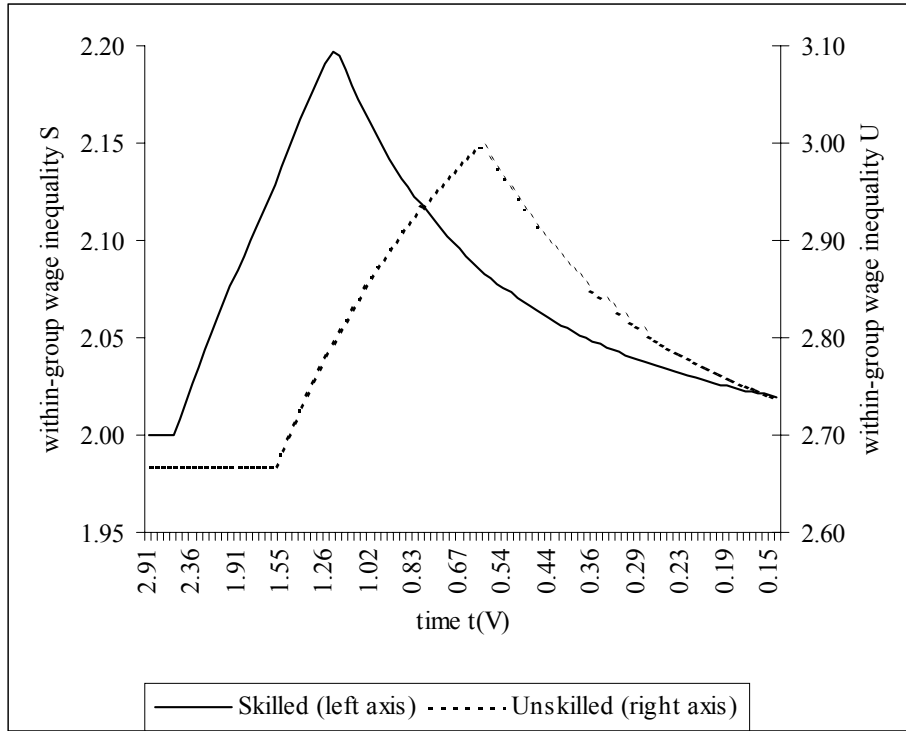
Figure 2
Relative Wages over Time
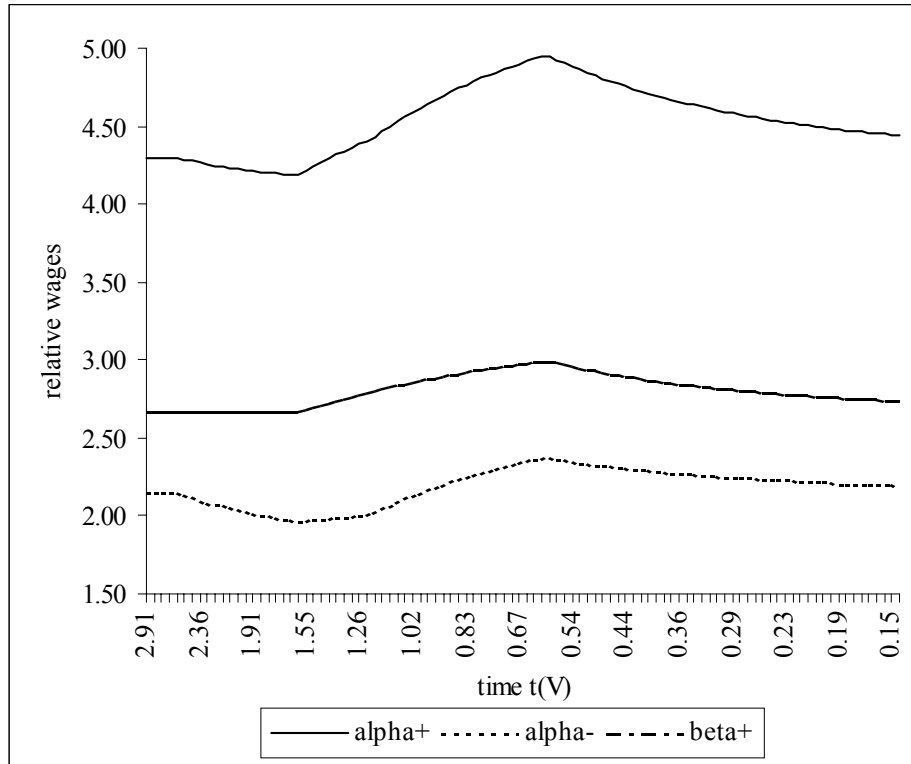
Note: The horizontal axis reports the falling cost of computers as a function of time. The costs of computers are assumed to fall according to the following relationship: $V_t = A e^{-Bt}$, where the following parameters are used: $A = 3$ and $B = .03$. To generate Figure 2, the following parameters are assumed: $S=100$, $U=200$, $\rho=.3$, $\chi = \psi = 1$, $\bar{\alpha} = 10$, $\underline{\alpha} = 5$, $\bar{\beta} = 8$, $\underline{\beta} = 3$ and $\theta^s = \theta^u = 1.2$.

Figure 3

Between-Group Wage-Inequality over Time for Differences in Proportional Productivity
Gains for Skilled and Unskilled Workers
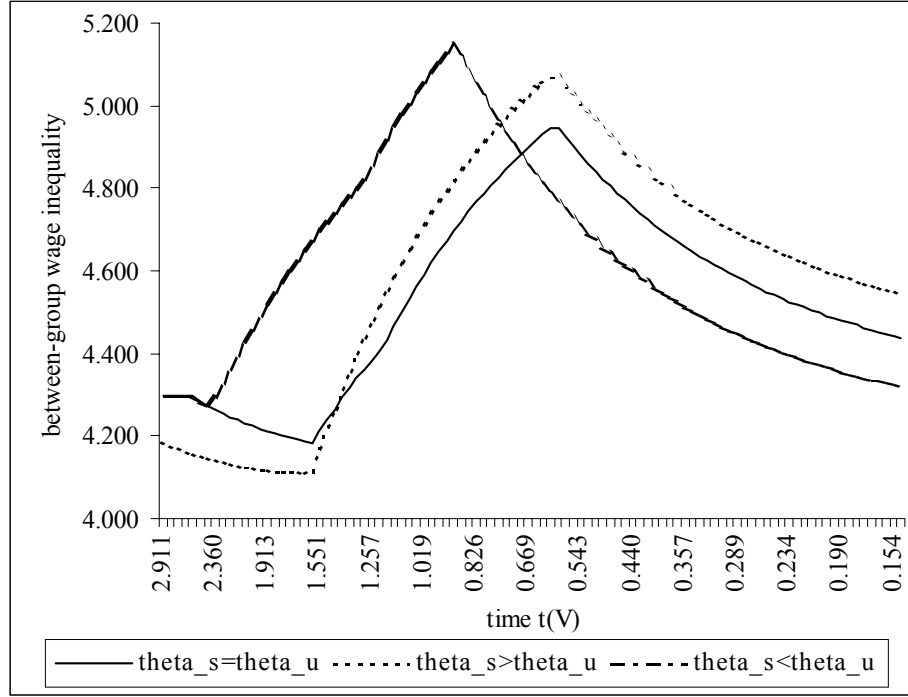
Note: The horizontal axis reports the falling cost of computers as a function of time. The costs of computers are assumed to fall according to the following relationship: $V_t = A e^{-Bt}$, where the following parameters are used: $A = 3$ and $B = .03$. To generate the lines in Figure 3, the following parameters are assumed if $\theta^s = \theta^u$: $S = 100$, $U = 200$, $\rho=.3$, $\chi = \psi = 1$, $\bar{\alpha} = 10$, $\underline{\alpha} = 5$, $\bar{\beta} = 8$, $\underline{\beta} = 3$ and $\theta^s = \theta^u = 1.2$. if $\theta^s > \theta^u$, the same parameters are included except $\theta^s = 1.3$. If $\theta^s < \theta^u$, the same parameters are used but $\theta^s = 1.2$ and $\theta^u = 1.3$.

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Figure 4
The Timing of Within-Group Wage-Inequality

Note: The horizontal axis reports the falling cost of computers as a function of time. The costs of computers are assumed to fall according to the following relationship: $V_t = A e^{-Bt}$, where the following parameters are used: $A = 3$ and $B = .03$. To generate Figure 4, the following parameters are assumed: $S=100$, $U=200$, $\rho=.3$, $\chi = \psi = 1$, $\bar{\alpha} = 10$, $\underline{\alpha} = 5$, $\bar{\beta} = 8$, $\underline{\beta} = 3$ and $\theta^s = \theta^u = 1.2$.

Figure 5
Imputed Computer Use in the United States 1963-2000
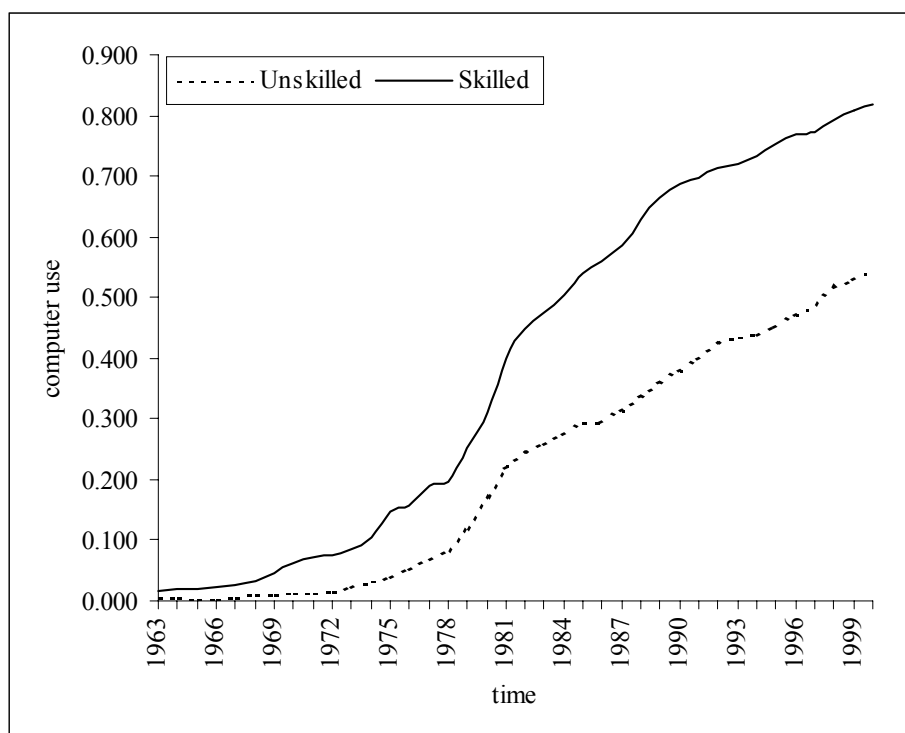
Note: All data are taken from the October CPS in 1984, 1989, 1993 and 1997 and the March CPS from 1964 to 2001. The imputed series for computer use are estimated using the October series on computer use and real wages to estimate a wage equation for the years in which computer use is available. This equation is used to impute computer use in the March series from 1964 to 2001.