Technological Change, the Labor market and the Stock Market

Rodolfo E. Manuelli*
Department of Economics. University of Wisconsin-Madison

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Abstract

This paper presents a model in which a partially anticipated technology shock results, in the short run, in lower investment and higher unemployment. Because of the expectation of future lower profits, the market value of existing firms —and the wages they pay— decreases before the new (better) technology becomes available. When the new technology arrives, the market value of new firms rises, average wages increase, but endogenous gradual adoption results in temporary wage dispersion among identical workers. The model shows that the same factors that affect the rate of adoption of a new technology also influence the cross sectional dispersion of labor earnings among identical workers, and the market value of business firms. The predictions of the model seem to be broadly consistent with the U.S. experience of the last thirty years.

1 Introduction

One view of the impressive increases in productivity during the late 1980's and especially the 1990s is that they are the result of the gradual adoption of a number of technologies sometimes referred to as the "informational technology" (IT) revolution. Even though widespread adoption did not start until the 1980s, the nature of the technology could be anticipated at least a decade earlier. The 1970s, however, were characterized by a lackluster performance of investment and productivity, and by a sluggish labor market (slow growth in total compensation and high unemployment). In addition, the stock market declined at the same time that the earnings price ratio increased significantly.

This paper explores the impact upon the labor and the stock markets of the existence of a lag between the time at which a major invention or discovery is identified, and the time at which it is used in production. Thus, in this view, the

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process of incorporating a new major technology consists of two phases: *Phase I* corresponds to the period after the major discovery, but before it becomes practical to adopt it (i.e. before the technology is mature). *Phase II* starts when the new discoveries are "usable" as (more productive) mature technologies in production.

This paper argues that this lag, coupled with a model of employment and investment frictions, can account for:

- High unemployment, low real wages, low investment, and a low market value of existing firms, during *Phase I.*
- Increases in average wages, investment, and the market value of firms, and decreases in unemployment during *Phase II.*
- Increased cross sectional dispersion in labor income among identical workers, and in the market value of firms in the adoption phase.

To a first approximation, these features agree with some of the U.S. evidence of the last thirty years.[1]

I consider a model with two basic frictions: First, as in Mortensen and Pissarides (1994), there are matching frictions between workers and firms or technologies. Thus, it is not costless to reallocate workers to different firms. Second, more productive technologies are embedded in machines produced after the technology matures. Thus, the model is essentially of the vintage-capital variety.

The basic idea is simple. Suppose that, at $t = 0$, all agents learn that, at some random time in the future, a new, more productive, technology (embedded in new capital goods) will become available. Consider first what happens during the adoption phase (*Phase II*). If firms using the old technology are to compete with firms using the new technology after the new technology becomes available, they will have to pay higher wages because of competition in the labor market. However, given the costs of reallocating workers across firms, wages paid by the old technology firms need not equal wages paid by the firms that adopt the new technology. Thus, the arrival of the new technology increases —temporarily— wage inequality.

What happens during the period before the new technology becomes available? Firms' market values will drop —because of anticipated lower profits due to future higher wages— and, with them, the wages they are currently willing to pay. Moreover, firms entering the industry during *Phase I* have to adopt the old technology, as the new technology is not yet available. Thus, these firms knowingly choose technologies that they know will be obsolete. Since their future profits will be low, there are few entrants. This results in low investment and job creation, which contributes to an increase in unemployment. These effects

[1] Relatively sluggish behavior of productivity before a period of significant growth also characterizes the early decades of the 20th Century. In this case, the "dynamo revolution" generated qualitative features that are similar to those of the IT revolution. See, for example, David and Wright (1999).

are stronger the more productive the technology or the sooner it is expected to arrive.

Thus, an anticipated technological innovation results, in the short run, in weak labor (low wages and high unemployment) and stock markets (low market value of firms and high earnings price ratios). The arrival of the new technology signals the beginning of a recovery in both markets. However, this recovery is associated with higher dispersion or earnings among identical workers, and among firms. The rate of adoption, and the degree of earnings and market value inequality, depend on the nature of the technological shock, with better technologies associated with faster adoption and more dispersion.

In some dimensions this paper complements the existing literature on the effects of major technological innovations; in some other dimensions, it emphasizes an alternative mechanism through which technical change influences economic performance. It complements work by Atkeson and Kehoe (1997), Greenwood and Yarukoglu (1997), Greenwood (1997), Caselli (1999), Greenwood and Jovanovic (1999), Jovanovic and Hojbin (2000) and Acemoglu (2000) since it explains three important observations that are not considered in those papers: It accounts for the dynamics of unemployment; it shows that vintage capital effects can generate transitory increases in, within skill group, wage dispersion, and it argues that developments in labor and stock markets are related.

Atkeson and Kehoe (1997) study the dynamics of adoption of a new technology. Their central argument is that new organizational capital is needed to use the new technology, but that this form of capital is not measured in the National Income and Product Accounts. Measured —but not real— output decreases before the technology is widely adopted. Greenwood and Yarukoglu (1997) also view the period before the widespread adoption of the new technology as a period of unmeasured investment. In their case is investment in "learning how to use the new technology." Since this form of investment does not appear in conventional measures of output, output decreases. In addition, adoption of new technologies requires, initially, more resources and, hence, results in lower productivity. Their model implies that the wages of skilled individuals —those that can learn how to use the new technology— decrease in the first phase of the technological revolution since, even though those workers are better at learning how to use new technologies, their productivity is initially low. Over time, network externalities result in an a decrease in the cost of adoption, and real wages increase. Since high skill workers are better at learning than low skill workers, their relative wages increase, with some overshooting in the first phase of a technological revolution. In both the Atkeson and Kehoe (1997) and the Greenwood and Yarukoglu (1997) models stock markets should be able to "see" through the measurement problems that the NIPA cannot deal with. In other words, the market value of adopters should increase as soon as the technology is available and this is well before productivity increases. It does not seem that the stock market evidence during the last 30 years is consistent with this implication of their models.

Caselli (1999) considers a model in which the transition takes one period, which he interprets as a generation. In his model, real wages do not decline, and the increase in wage dispersion is driven by individual differences in the cost of adapting to new technologies. Thus, in this sense, his is also a model of the skill premium, only that in his model skill is not observed. In Caselli (1999) the onset of the technological revolution results in a change in a composition of investment, but not a decrease. Finally, as in Greenwood and Yarukoglu (1997) and Atkeson and Kehoe (1997) there is no unemployment, and the market value of firms should increase before the increase in productivity.

Acemoglu (2000) surveys a variety of models that explain the rise of the skill premia. In addition, to the standard arguments that emphasize exogenous changes in the skill requirement, he discusses the endogenous determination of the "technological bias," with an emphasis on the impact that the availability of high skill workers has on the profitability of developing technologies that use those skills intensively.

This paper proposes a very different mechanism to understand the short and long-run effects of a major technological innovation: anticipation effects increase the option value of waiting to invest and ,consequently, investment decisions are delayed. This same mechanism influences the endogenous rate of adoption and, hence, the degree of earnings inequality. Thus, the key mechanisms is lower investment, and not unmeasured investment.

There are other dimensions in which the two approaches differ. The model of this paper —contrary to Greenwood and Yarukoglu (1997) and Caselli (1999)— implies that, in the period before to the adoption of the new technology, the value of existing firms should decrease, while the arrival of the technology should increase the value of "new technology" firms and decrease the value of "old technology" firms. This stylized description of the asset market impact of a technological revolution broadly agrees with the findings of Greenwood and Jovanovic (1999), and Jovanovic and Hojbin (2000). Finally, my model implies that the effective availability of the new technology coincides with a gradual increase in the market value of firms and in investment, a rise in average wages, and a transitory increase in the within skill group wage dispersion.

Section 2 describes the model, and Section 3 details its implications for the labor and stock markets. Section 4 introduces heterogeneity across sectors, and Section 5 describes some macro evidence. Finally, Section 6 discusses extensions and offers some conclusions.

2 Basic Model

In this section I present the model. I then study its equilibrium and I discuss how productivity changes affect the relevant labor market variables. I then analyze the transition effects of a partially anticipated technological revolution.

I use a simple matching model along the lines of Mortensen and Pissarides (1994). Time is continuous and there is a potentially large number of firms of unbounded measure. There is also a large number of workers with total measure equal to one. Population is constant. Workers and firms cannot be matched costlessly. If v vacancies are created, and u workers are unemployed, the total number of matches is given by $M(u, v)$. I assume that M is homogeneous of degree one, increasing in each argument, and differentiable. Let θ be the ratio of vacancies to unemployed workers, and denote by $q(\theta)$ the number of matches per vacancy; thus, $q(\theta) \equiv M(u, v)/v$. Then, $q(\theta)dt$ is the probability that in a small interval of time of length dt a firm will meet a worker; moreover, $q'(\theta) < 0$, and $\lim_{\theta \to 0} q(\theta) = \infty$. Conversely, $\theta q(\theta)dt$ is the probability that a worker who is unemployed —and only the unemployed can "contact" firms— will find an open vacancy. The term $\theta q(\theta)$ is increasing in θ, goes to 0 as θ decreases to 0, and it grows without bound as θ goes to ∞.

If a firm and a worker are matched, the match produces y units of output. In order to create a job, a firm must purchase k units capital. This capital must be purchased up front but can be costlessly sold or upgraded *before* the firm finds a worker. After the match is created, capital has no scrap value.[2] Existing matches, if not dissolved by firms or workers, last a random number of years. The distribution of the (exogenous) lifetime of a match is exponential with parameter η. Finally, the interest rate, r, is constant, and it is assumed that both workers and firms are risk neutral.

Let J be the value of a job (which in this model it is also the value of an existing firm), and V the value of being able to create a vacancy. Given the structure of the model, in the absence of shocks, all variables —except the unemployment rate, the only state variable— immediately jump to their steady state levels. Thus, to simplify the presentation, I focus only on the steady state version of the problems faced by firms and workers. Assuming that matches are never voluntarily destroyed (this will be the case in equilibrium) the value of a firm that pays wages w satisfies the following Bellman's equation,

$$rJ = y - w + \eta(V - k - J), \tag{1}$$

$$rV = 0 + q(\theta)(J - V). \tag{2}$$

Workers who are not matched to firms produce z units of output. Assume that $y > z$, since otherwise no output is produced in the market sector. Let E be the value of being employed and U the value of being unemployed. Then, Bellman's equation for the worker's problem satisfies,

$$rE = w + \eta(U - E), \tag{3}$$

$$rU = z + \theta q(\theta)(E - U). \tag{4}$$

Finally, I assume that wages are determined following a Nash bargaining procedure between matched workers-firms pairs, with the workers' bargaining power given by ϕ, for some $0 < \phi < 1$. This implies that the excess value of being employed, $E - U$, equals ϕS, where $S \equiv J + E - U - (V - k)$ is the total surplus of the match, while the value of an ongoing firm satisfies

[2] The assumption of perfect malleability before the match is created simplifies the dynamic analysis as it allows vacancies to be created or destroyed instantaneously. Incorporating irreversibilities at the pre-match stage or reducing the specificity at the post match destruction state adds transitional dynamics without affecting the results.

$J-(V-k)=(1-\phi)S$. This assumption, which is standard in the matching literature, is not innocuous, as the welfare properties of the equilibrium depend on the shape of the $q(\theta)$ function and the parameter ϕ. However, it greatly simplifies the presentation, and does not affect (some of) the major qualitative conclusions.

2.1 The Steady State Equilibrium

In this section I describe the steady state equilibrium. Since the model is standard, the presentation will be brief. In an equilibrium with free entry, the net value of being able to post a vacancy is zero. Thus $V=k$. Using this in (1) and (2) it follows, that

$$J=(r+q(\theta))k/q(\theta), \tag{5}$$

$$w=y-(r+\eta)(r+q(\theta))k/q(\theta). \tag{6}$$

Since $1/q(\theta)$ is the expected time until a vacancy is filled, the equilibrium value of an ongoing firm is just the initial investment, k, plus the interest cost of the capital per period, rk, times the expected number of periods. Thus, $(r+q(\theta))k/q(\theta)=k+rk/q(\theta)$ is just total investment cost until the firm is fully productive. Equation (6) describes the pairs of wages and probability of filling a vacancy that are consistent with zero profits. In the (θ,w) plane this relationship is downward sloping: a higher wait time to fill a vacancy —corresponding to a higher ratio of firms per worker, θ— requires lower wage payments when the firm finds a worker.

Since $V=k$, the surplus generated by the match is $S=J+E-U$. Using (1) - (4), it follows that S obeys the following Bellman's equation,

$$(r+\eta+\theta q(\theta))S=y-z+\theta q(\theta)J,$$

and using (5) one obtains,

$$(r+\eta+\theta q(\theta))S=y-z+\theta(r+q(\theta))k. \tag{7}$$

Next, (3) and (4) imply that the excess value of being employed satisfies,

$$(r+\eta+\theta q(\theta))(E-U)=w-z. \tag{8}$$

Since Nash bargaining implies that $E-U=\phi S$, (7) and (8) imply,

$$w=z+\phi[y-z+\theta(r+q(\theta))k]. \tag{9}$$

The change in the unemployment rate at time t, $\dot{u}_t$, is given by the difference between the number of jobs created, $\theta q(\theta)u_t$, and the number of jobs destroyed, $\eta(1-u_t)$, and it satisfies the following differential equation,

$$\dot{u}_t=\eta(1-u_t)-\theta q(\theta)u_t. \tag{10}$$

In a steady state equilibrium $\dot{u}_t = 0$, and the unemployment rate is

$$u = \frac{\eta}{\eta + \theta q(\theta)}, \tag{11}$$

which is decreasing in θ.

An equilibrium is a vector (J, w, E, U, θ) and a function u_t that satisfy all the above equations. For an equilibrium to exist it is necessary (and it turns out sufficient as well) that the firm's share of the present discounted value of the total physical surplus of the match, $(1-\phi)(y-z)/(r+\eta)$, has to exceed the cost of investing in a new firm, k. Thus, from now on I assume

Condition 1 (A) $(1-\phi)(y-z)/(r+\eta) > k$

In this economy, the equilibrium can be computed recursively. First, equations (6) and (9) can be used to solve for the equilibrium values of (w, θ). Given the assumptions, the solution is unique. Then, the valuations (both for workers and firms) can be computed by solving (1) - (4) and, finally, the process for the unemployment rate is the solution to (10). This economy displays no dynamics except for the unemployment rate. Thus, given any initial level of unemployment, the economy immediately jumps to the steady state values of the vector (J, w, E, U, θ). Of course, the unemployment rate does not jump, and follows (10).

2.2 Phase II: Technology Adoption

Let the economy before time 0 be described by starred variables. Thus, productivity is given by y^*, and an equilibrium is a vector $(J^*, w^*, E^*, U^*, \theta^*)$ and an unemployment rate u_t^*. Suppose that, at time 0, it is learned that at some (random) time in the future each newly created firm will have productivity $\hat{y} > y^*$.[3] It is assumed that this higher productivity is embedded in new capital goods. In particular, this implies that firms that already have a worker in place before the new technology becomes available cannot upgrade. This assumption is extreme, but the results go through without any changes if, alternatively, it is assumed that existing firms have to find new workers after they acquire the new technology.[4] Let the distribution of the arrival time of the new technology be exponential with parameter μ. I denote the realization of this random variable by T.

The period from $t = 0$ —when information about the new technology arrives— to $t = T$ —when it becomes available for productive use— corresponds to *Phase I.* At time T, *Phase II* starts. At this point every newly created firm adopts the more productive technology.

I will denote the equilibrium values of all relevant variables after time T with a hat. What happens at time T? The key observation is that the equilibrium

[3] Formally, this is equivalent to assuming that the new technology is embedded in new capital goods; the standard vintage capital assumption.

[4] Even if the exisitng workers can be retained and the firm can convert, at a cost, to the new technology, the major qualitative results of the paper remain unchanged.

level of θ, $\hat{\theta}$, and the equilibrium wage of workers employed in the new technology, $\hat{w}_1$, are completely determined by (6) and (9). The argument is simple: The derivation of (6) simply requires that newly formed firms have expected net present value equal to zero. Thus, it is possible for existing firms to have a market value that is less than their (already sunk) investment. Will firms using the old technology continue operating? The answer is positive provided that their value as an ongoing concern (after their workers' wages are adjusted) is still positive, since the value of liquidating is zero (due to free entry).

Similarly, the derivation of (9), the second equation used to calculate the basic equilibrium variables, relies exclusively on the properties of the problem faced by an unemployed worker at time T. Since *all* unemployed workers will be matched with the newly formed firms (which adopt the new technology), the relevant variables are the "hat" variables.

Let the wage paid by a high technology firm be denoted $\hat{w}_1$. It follows from (6) and (9) that $\hat{w}_1 > w^*$, and that $\hat{\theta} > \theta^*$. Thus, the arrival of the new technology results in an increase in real wages for the workers matched with it. Also, in the long run, the unemployment rate, $\hat{u}$, satisfies the relevant version of (11), and is lower than u^*.

What happens to existing (old technology) firms at T? The only relevant (to them) change is that their workers now face a higher opportunity cost of being employed. If a worker quits, he/she will receive utility $\hat{U}$, where $\hat{U}$ depends on $\hat{w}_1$. Let a subscript 0 denote the variables corresponding to the firm-worker pairs that operate the *old* technology after time T. Then, the relevant version of Bellman's equation for firms and workers is (if no matches are destroyed),

$$\begin{aligned} r\hat{J}_0 &= y^* - \hat{w}_0 + \eta(\hat{V} - \hat{J}_0 - k), \\ r\hat{E}_0 &= \hat{w}_0 + \eta(\hat{U} - \hat{E}_0), \\ r\hat{U} &= z + \hat{\theta}q(\hat{\theta})(\hat{E}_1 - \hat{U}). \end{aligned}$$

The first equation simply captures the idea that the value of the firm is the instantaneous value of profits, $y^* - \hat{w}_0$, plus the capital loss associated with liquidation, $\eta(\hat{V} - \hat{J}_0 - k)$. Note that, since $\hat{\theta} > 0$, new firms are entering, and, hence, $\hat{V} = k$. The second equation captures the same idea for workers. In this case, the opportunity cost of quitting, $\eta(\hat{U} - \hat{E}_0)$, depends on the value of being unemployed which, in turn, depends on the wages paid by firms using the new, high productivity technology.

In order to guarantee that an equilibrium in which no firms stop production exists, it suffices to assume that the interest cost of initial investment after the new technology becomes available exceeds the firms' share of the present discounted value of the productivity gain. Formally this corresponds to,

Condition 2 (B) $\frac{r+q(\hat{\theta})}{q(\hat{\theta})}k > \frac{(1-\phi)(\hat{y}-y^*)}{(r+\eta)}$.

This assumption simply says that the value of an ongoing firm with the new technology —$(rq(\hat{\theta})^{-1}+1)k$— exceeds the firm's share of the present discounted value of switching to the new technology.

Proposition 3 *Given Assumptions* (A) *and* (B),

i) It is optimal for firms and workers operating the old technology not to liquidate.

ii) Wages of workers using the old technology, $\hat{w}_0$*, satisfy,* $\hat{w}_0 = \hat{w}_1 - \phi(\hat{y} - y^*)$.

iii) $\hat{w}_0 > w^*$.

Proof. See Appendix. ■

Thus, following the introduction of the new technology, identical workers receive different wages. The reason lies in the friction that is used to model labor markets: it is costly to destroy matches. However, the model implies that the existence of a new technology affects immediately the wages received by all the workers matched with old technology, independently of the fraction of firms that use the new technology. More precisely, at time T, the fraction of firms using the advanced technology is zero. Nevertheless, the availability of such a technology forces all firms to immediately increase wages. Even "unlucky" workers —those matched to old technologies— receive wages that exceed those of the pre technological revolution period. Finally, the model implies that the wage differentials are related to the size of the technology gap: the more substantial the technological revolution the higher the degree of wage inequality.

2.3 Phase I: Anticipation Effects

What happens at time 0? Let's denote the relevant variables during *Phase I* —the interval $[0, T)$— with a tilde. Standard arguments can be used to show that the relevant Bellman's equations —the analogues of (1)-(4)— must satisfy,

$$r\tilde{J} = y^* - \tilde{w} + \eta(\tilde{V} - \tilde{J} - k) + \mu(\hat{J}_0 - \tilde{J}), \qquad (12)$$

$$r\tilde{V} = 0 + q(\hat{\theta})(\tilde{J} - \tilde{V}) + \mu(\hat{V} - \tilde{V}), \qquad (13)$$

$$r\tilde{E} = \tilde{w} + \eta(\tilde{U} - \tilde{E}) + \mu(\hat{E}_0 - \tilde{E}), \qquad (14)$$

$$r\tilde{U} = z + \tilde{\theta}q(\tilde{\theta})(\tilde{E} - \tilde{U}) + \mu(\hat{U} - \tilde{U}). \qquad (15)$$

The intuition is simple. Consider, for example, the flow value of a firm, $r\tilde{J}$. It equals the value of instantaneous profits, $y^* - \tilde{w}$, plus the capital gain (a loss in this case) associated with liquidation, $\eta(\hat{V} - \tilde{J} - k)$, plus the capital gain (or loss) associated with the arrival of the new technology, $\mu(\hat{J}_0 - \tilde{J})$. If the new technology arrives, the value of this firm will be given by $\hat{J}_0$, since, as was shown before, it will have to pay higher wages, but it will continue to operate.

If there is entry during *Phase I* —which is guaranteed by the assumptions on $q(\theta)$— it must be that $\tilde{V} = k$. In this case, it follows that the analog of (5) holds and,

$$\tilde{J} = \frac{(r + q(\tilde{\theta}))k}{q(\tilde{\theta})} = k + r\frac{k}{q(\tilde{\theta})}. \qquad (16)$$

It follows from (12) - (15) that

$$\tilde{w} = y^* - (r + \eta + \mu)\frac{(r + q(\tilde{\theta}))k}{q(\tilde{\theta})} + \mu\hat{J}_0$$

or,

$$\tilde{w} = y^* - (r+\eta)\frac{(r+q(\tilde{\theta}))k}{q(\tilde{\theta})} + \mu(\hat{J}_0 - \frac{(r+q(\tilde{\theta}))k}{q(\tilde{\theta})}). \tag{17}$$

Next, using (12) - (15), as before, it is possible to derive an equation for the total value of the surplus generated by a match during *Phase I*. The surplus, given by $\tilde{S} = \tilde{J} + \tilde{E} - \tilde{U}$, satisfies the appropriate version of (7),

$$(r+\eta+\mu+\tilde{\theta}q(\tilde{\theta}))\tilde{S} = y^* - z + \tilde{\theta}(r+q(\tilde{\theta}))k + \mu\hat{S}_0, \tag{18}$$

where $\hat{S}_0$ is the surplus associated with a match using the old technology after the new technology becomes available, that is, in my notation, after time T. From, (13) and (14) it follows that,

$$(r+\eta+\mu+\tilde{\theta}q(\tilde{\theta}))(\tilde{E}-\tilde{U}) = \tilde{w} - z + \mu(\hat{E}_0 - \hat{U}) = \tilde{w} - z + \mu\phi\hat{S}_0,$$

where the equilibrium condition $\hat{E}_0 - \hat{U} = \phi\hat{S}_0$ was used. It is immediate that this equation and (18) imply that, to satisfy Nash bargaining, the wage rate has to be given by,

$$\tilde{w} = z + \phi[y^* - z + \tilde{\theta}(r+q(\tilde{\theta}))k]. \tag{19}$$

As before, it is now possible to compute the equilibrium during *Phase I* by first solving (17) and (19). Note that (19) is similar to (9), while (17) equals (6) minus $\mu[\tilde{J} - \hat{J}_0]$, where this last result follows from (16). Thus, if the value of a firm using the old technology before the new technology becomes available, $\tilde{J}$, exceeds the value of the same firm after the introduction of the new technology, $\hat{J}_0$, then the downward sloping curve given by (17) must lie below (6). It then follows that, relative to (w^*, θ^*) —the equilibrium values during *Phase I*— the new equilibrium is characterized by lower wages, $\tilde{w} < w^*$, and fewer vacancies per unemployed worker, $\tilde{\theta} < \theta^*$. Proposition 4 shows that this is indeed the case. Here, I offer some simple intuition. The reason why $\tilde{J}$ is greater than $\hat{J}_0$ is because, during *Phase I*, competition from the new technology is a future (and hence discounted) and uncertain event. As such, it has a smaller impact upon profits than the contemporaneous availability of a better technology. The latter effect is fully captured by $\hat{J}_0$. Since during *Phase I* all firms have the same technology, there is no wage dispersion. The equilibrium during this period is characterized by the following result:

Proposition 4 *Assume that conditions* (A) *and* (B) *hold. During* Phase I *the equilibrium wage,* $\tilde{w}$*, and market tightness,* $\tilde{\theta}$*, satisfy:*
i) $w^* > \tilde{w}$.
ii) $\theta^* > \tilde{\theta}$.

Proof. See the Appendix. ■

Thus, wages fall at the time that the market learns about the future availability of the new technology. This decrease is driven by the lower value of the match, given the (correct) expectation that future wages will be higher. At $t = T$, the arrival of the new technology has two effects: it reduces even more the surplus associated with existing matches as "potential" competition turns into actual competition; in addition, it also increases the value of being unemployed. The first effect tends to depress wages of workers matched to old technologies, while the second raises them. In this model the competition effect is stronger, and the wage rate increases following the introduction of the new technology.

Phase I is also characterized by a lower ratio of vacancies to unemployed workers. The reason is simple: the value of a job created during this period —which uses the old technology— is low because it is known that, when the new technology arrives, newly created firms will be more productive. Since, in equilibrium, the value of a newly created job must equal its cost $(k + rk/q(\tilde{\theta}))$, the cost of creating a firm must decrease. This can only be accomplished by a reduction in the time between the capital stock is purchased, and the time the firm is operational. On average, that time equals $1/q(\tilde{\theta})$. Thus a lower value of θ (a higher value of $1/q(\theta)$) decreases effective costs of investment.

3 Dynamics

In this section I describe the dynamics implied by the model.

3.1 Unemployment

As indicated before, the unemployment rate satisfies (10)[5]. Without loss of generality I assume that, at time 0, the economy is at its steady state with unemployment rate given by $u^* = \eta/(\eta + \theta^* q(\theta^*))$. At $t = 0$, there is a decrease in the rate of job creation from $\theta^* q(\theta^*)$ to $\tilde{\theta} q(\tilde{\theta})$, and this lower rate prevails until time T —random as of time 0— at which point the job creation rate increases to $\hat{\theta} q(\hat{\theta}) > \theta^* q(\theta^*)$. Thus, $\dot{u}_t > 0$ for $t \, \epsilon \, (0, T)$, and $\dot{u}_t < 0$ for $t > T$. Thus, the model implies an increase in the unemployment rate during *Phase I* of the technological revolution, and a decrease afterwards. A typical path is shown in Figure 1.

The reason for the increase in unemployment during the transition is simple: in anticipation of the arrival of the new technology, the market value of existing firms decreases. This discourages investment in job creation which, in turn, results in an increase in unemployment. A key implication of the model is that knowledge that a better technology will be available induces a delay in investment decisions. Thus, unlike the models based on learning by doing, the sluggishness in *Phase I* is not due to unmeasured investment; on the contrary, it corresponds to low investment.

The model is too simple for job destruction to respond to the change in market conditions. Taking into account this limitation, the model implies that at $t = 0$, the ratio between the job destruction rate and the job creation rate, accounted by for new entrants and firms exiting only, has a peak. During *Phase*

[5] Formally, one should define the process followed by the unemployment rate by a stochastic differential equation driven by a jump process with parameter μ. This, however, does not add economic intuition. Thus, the formal details will be ignored.

I, this ratio decreases but it remains above one. At time T, there is a drop in the ratio, followed by sustained increases.

3.2 Employment

In this model, employment is just $1 - u_t$. Thus, as the previous section showed, employment decreases during *Phase I* of the technological revolution. Let employment at time T be n_T. Note that for $t > T$, firms using the old technology do not hire any more workers, and the sector as a whole destroys jobs at the rate η. On the other hand, all new employment occurs in the high productivity firms. Let n_{0t} and n_{1t} denote employment in the old and new technologies, respectively. Then, after time T, the evolution of employment in each of the two technologies is governed by a pair of differential equations given by,

$$\dot{n}_{0t} = -\eta n_{0t} \tag{20a}$$

$$\dot{n}_{1t} = -\eta n_{1t} + \hat{\theta} q(\hat{\theta})(1 - n_{0t} - n_{1t}) \tag{20b}$$

where the second equation shows that the total change in the number of individuals employed in the high productivity firms equals total employment creation, $\hat{\theta} q(\hat{\theta})(1 - n_{0t} - n_{1t})$, minus sector specific job destruction, ηn_{1t}. The system of equations (20) is to be solved subject to the initial condition that, at $t = T$, $n_{0T} = n_T$, and that $n_{1T} = 0$. The solution is given by,

$$\begin{aligned} n_{0t} &= n_T e^{-\eta(t-T)} \\ n_{1t} &= \hat{n} - n_T e^{-\eta(t-T)} - (\hat{n} - n_T) e^{-(\eta + \hat{\theta} q(\hat{\theta}))(t-T)}, \end{aligned}$$

where $\hat{n} = \hat{\theta} q(\hat{\theta}) / [\eta + \hat{\theta} q(\hat{\theta})]$ is the long run level of employment. Given the behavior of unemployment, $n_T < \hat{n}$. Thus, employment in the low productivity sector decreases, while employment in the high productivity sector increases. For future use, note that the fraction of employment in low productivity sector is given by, π_t, where

$$\pi_t = \frac{n_T e^{-\eta(t-T)}}{\hat{n} - (\hat{n} - n_T) e^{-(\eta + \hat{\theta} q(\hat{\theta}))(t-T)}} \tag{21}$$

is decreasing. Finally, note that the fraction of firms using the new technology —the diffusion rate— is just $a_t = 1 - \pi_t$, and it displays the upward sloping S shape identified in many empirical studies.[6]

3.3 Wages and Productivity

First, consider the implications of the model for average wages, $\bar{w}_t$. Before *Phase I*, average wages are given by w^*. At time 0, they drop to $\tilde{w}$, and this average remains unchanged until time T. At that point average wages jump down to $\hat{w}_0$

[6] See Gort and Klepper (1982), Jovanovic and Llach (1997) and Greenwood (1997) among others.

and increase steadily to $\hat{w}_1$. During this period (after time T) average wages obey,

$$\bar{w}_t = \hat{w}_0 \pi_t + (1 - \pi_t)\hat{w}_1 = \hat{w}_1 - \pi_t \phi(\hat{y} - y^*).$$

The model implies that, during *Phase I*, average wages decrease even though productivity does not change. This, as I will argue below, is accompanied by a decrease in the market value of existing firms, and an increase in the earnings-price ratio.

What does the model imply for wage dispersion? Since the economy formally has only one type of worker, the relevant measure of variability is within skill (or education) wage dispersion. The results show that until time T, the cross sectional variance of wages is zero. Simple calculations show that for $t \geq T$, the cross sectional variance of wages is given by,

$$\sigma_{wt}^2 = (\phi(\hat{y} - y^*))^2 \pi_t (1 - \pi_t). \tag{22}$$

It follows that during *Phase II*, the model implies that the cross sectional dispersion of wages has, as a function of time, an inverted U shape. This is another distinct implication of the model: the within skill cross sectional variability of wages does not increase until the new technology is adopted, and even then the increase is temporary. In the long run —and in the absence of another "revolution"— all workers are employed in the high productivity firms. A typical path for average wages and its dispersion is presented in Figure 1.

Finally, it is possible to compute the between plants dispersion in productivity levels. The model implies that the levels of wage, σ_{wt}, and productivity, σ_{yt}, dispersion are related by

$$\sigma_{yt} = \phi^{-1} \sigma_{wt}. \tag{23}$$

Thus, increases in the dispersion of within skill wages is accompanied by increases in the between plants dispersion in labor productivity.

3.4 Market Value of Firms

Let the market value of an ongoing firm using the old technology at time t, J_t[7], is given by

$$J_t = \begin{cases} J^* & t < 0, \\ \tilde{J} & t \in [0, T) \\ \hat{J}_0 & t \geq T \end{cases}$$

while the value of a firm using the new technology is zero before time T, since the option to create one is worthless given free entry, and $\hat{J}_1$ after T. It follows that,

Proposition 5 *The market value of existing firms satisfies* $\hat{J}_0 < \tilde{J} < J^* < \hat{J}_1$.

[7]This interpretation of J_t assumes that all firms are equity financed. This, is extreme but unless differences in the debt-equity ratio are consistently associated with technological adoption, the same qualitative implications remain.

Proof. See the Appendix. ■

Thus, the market value of incumbent firms —in this case firms using the old technology— decreases before the technological revolution increases the productivity of new firms. It follows that the market value of incumbents decreases, without any increase in the value of yet to be created firms. At the time of the arrival of the high productivity technology, T, there is a further decrease in the value of the stock market. The reason is simple: at $t = T$, 100% of the firms are of type 0 —incumbents— and their value decreases from $\tilde{J}$ to $\hat{J}_0$. After time T, the average market value of firms increases, since a larger fraction of matches uses the high productivity technology. Figure 2 shows the implications of the model for both incumbents and entrants.

Let m_t be the *earnings-price ratio.* In this simple model, it is given by $m_t = (y_t - w_t)/J_t$. It follows from (5) and (6) that $m^* = \hat{m}_1 = r + \eta$. Simple calculations also show that $\hat{m}_0 = (y^* - \hat{w}_0)/\hat{J}_0$ also equals $r + \eta$. Finally, (17) implies that $\tilde{m} = r+\eta+\mu(\tilde{J}-\hat{J}_0)/\tilde{J}$, which is greater than $r+\eta$. Thus, the model predicts that during *Phase I* of the technological revolution the earnings-price ratio increases, and it returns to its "normal" value after the new technology is introduced. The predictions of the model for the earnings-price ratio are displayed in Figure 2.

The share of market capitalization corresponding to the new technology firms, κ_t $(t \geq T)$ is given by,

$$\kappa_t = \frac{a_t \hat{J}_1}{\hat{J}_1 - (1-a_t)(1-\phi)\frac{\hat{y}-y^*}{r+\eta}},$$

where $a_T = 0$, and $\lim_{t\to\infty} a_t = 1$. Thus, the share of new vintage (or new technology) firms increases monotonically during the adoption phase.

Finally, the model also has predictions about the time path of the ratio of the total value of business firms to output, which I denote z_t, and which are summarized in the following Proposition.

Proposition 6 *There exist values z^* and $\hat{z}$, with $\hat{z} > z^*$ such that the value of firms relative to output, z_t, satisfies*

$$z_t = \begin{cases} z^* & t < 0 \\ z_t < z^*,\ \dot{z}_t < 0 & 0 \leq t < T \\ \dot{z}_t > 0,\ \lim_{t\to\infty} z_t = \hat{z} & T \leq t \end{cases}$$

Proof. See the Appendix ■

Figure 3 shows that, using this measure, asset values do not recover their $t = 0$ levels until after T. Thus, the stock market lags increases in productivity. As before, this result is driven by the fact that the new —more productive— plants do not a large weight in total output at time T.

3.5 Investment

In the model, total investment is given by kv_t. Thus, investment per unit of market output (GDP) is just $x_t = k\theta_t u_t/\bar{y}_t$, where $\bar{y}_t$ is output per person. As before, consider an economy that, at $t = 0$, is at the steady state. At that point investment is given by $x^* = k\eta/[y^* q(\theta^*)]$. From $t = 0$ to $t = T$, investment satisfies, $\tilde{x}_t = k\tilde{\theta} u_t/[y^*(1 - u_t)]$. Simple calculations show that, $\tilde{x}_0 < x^*$, and that $\tilde{x}_t$ is increasing, but it always stays below x^*. At $t = T$, there is an upward jump in investment, which is now given by, $\hat{x}_T = k\hat{\theta} u_T/[y^*(1 - u_T)]$ or, $\hat{x}_T = k\hat{\theta}(1 - n_{0t} - n_{1t})/[y^* n_{0t} + \hat{y} n_{1t}]$, for $t \geq T$. Thus, from T on, investment is high and it converges to $\hat{x} = k\eta/[\hat{y} q(\hat{\theta})]$ which can be higher or lower than x^*. At this point, I cannot determine whether, at $t = T$ the investment - output ratio is increasing or decreasing.

Thus, the period after the new technology is first identified, but before it is mature enough to be used in production displays sluggish investment. The onset of the adoption phase, time T in the model, is characterized, on the other hand, with higher than average investment, which, however, decreases over time.

4 Heterogeneity

So far, I have assumed that technological change affects all sectors symmetrically. In this section, I allow sectors to vary both in the magnitude of the productivity improvement, $\hat{y}$, as well as in the speed at which the new technology is expected to arrive, μ.

Heterogeneity across sectors in the magnitude and pace of technological change reveals one more dimension in which labor and stock markets are connected: economic sectors which display higher cross-sectional variability of labor earnings will also display high variability in market value of firms. More precisely, for $t > T$, it follows that,

$$\sigma^i_{Jt} = \frac{1 - \phi_i}{\phi_i}(r + \eta)\sigma^i_{wt},$$

where σ^i_{wt} (σ^i_{Jt}) is the standard deviation of labor earnings (market value of firms) within sector i. Thus, controlling for labor's share (ϕ_i) the model predicts a positive relationship between the two measures of variability. Moreover, the model also implies that dispersion in productivity levels and wages across industries satisfies,

$$\sigma^i_{yt} = \phi_i^{-1}\sigma^i_{wt}.$$

Next, I study how differences in the stochastic process of technological change affects different sectors. To keep the analysis simple I assume that each sector has its own labor market.[8] First, consider the case in which each sector has its own $\hat{y}$, but all sectors share the same arrival time, T. The main results are:

Proposition 7 *Given conditions* (A) *and* (B)*:*
i) $\partial\hat{w}_1(\hat{y},\mu)/\partial\hat{y} > 0, \partial\hat{w}_0(\hat{y},\mu)/\partial\hat{y} < 0, \partial\tilde{w}(\hat{y},\mu)/\partial\hat{y} < 0,$
ii) $\partial\hat{J}_1(\hat{y},\mu)/\partial\hat{y} > 0, \partial\hat{J}_0(\hat{y},\mu)/\partial\hat{y} < 0, \partial\tilde{J}(\hat{y},\mu)/\partial\hat{y} < 0,$

[8] Allowing for a common labor market does not change the qualitative results but adds substantial complications to the analysis.

iii)$\partial a_t(\hat{y},\mu)/\partial\hat{y} > 0$,

iv) For t $(> T)$ *such that* $a_t \leq 1/2$, $\partial\sigma_{wt}(\hat{y},\mu)/\partial\hat{y} > 0$ *and* $\partial\sigma_{Jt}(\hat{y},\mu)/\partial\hat{y} > 0$.

Proof. See Appendix. ■

Thus, a higher level of improvement (higher $\hat{y}$) results in higher differences in wage rates between workers matched with the old and new technologies, and in higher differences in the market values of high and low technology firms.

The rate of adoption is also influenced by the magnitude of the productivity increase. High productivity industries tend to adopt the new technology faster than low productivity industries, and this results in higher levels of earnings (and market value) dispersion, at least in the initial stages of *Phase II*. Thus the model predicts positive correlation between rate of adoption (or growth in average productivity) and earnings dispersion.

In contrast to the positive impact of higher productivity levels in *Phase II*, the industries that will be more productive in the post-adoption period are the ones that suffer the most in the pre-adoption period. The higher the productivity level, the lower the wage rate in *Phase I* and the larger the drop in market value. The intuition for these results is the following: The more productive the future technology the less valuable the existing technology. Thus, the value of existing firms drops more when future firms will be more productive. This, in turn, results in lower wages, a lower rate of job creation, and a lower rate of investment.

Another dimension in which industries could differ is in the *duration* of *Phase I.* In other words, it is possible for some industries to rapidly adopt the new technology because it is relatively easy to integrate the new discoveries into the productive process, while in some other cases the necessary process of adaptation takes considerably longer. I capture these differences as differences in the arrival rate of the new technology, μ. Since the stochastic arrival process is different across sectors it does not seem reasonable to assume that the arrival time —T in the previous notation— is the same across sectors. I assume that, for each sector, $T = 1/\mu$, the mean arrival time.

Differences in μ across industries do not affect the post-adoption variables (except for the distribution of firms by type). Thus, $\hat{w}_1, \hat{w}_0, \hat{J}_1$, and $\hat{J}_0$ are independent of μ. On the other hand, heterogeneity in arrival times has an impact on how different industries fare in the short-run (*Phase I*), and in the levels of post-adoption volatility. High μ industries pay lower wages and see the market value of the firms in the industry drop more than low μ industries, since the existing old technology firms will face competition from the new firms sooner.

The effect of differences in arrival times on the post-adoption distribution of firms is driven by heterogeneity in the level of employment at the time the new technology becomes available, n_T, and in the time elapsed since T. A high μ has two effects on employment during the transition. First, it reduces the "long run" level of *Phase I* employment in the industry (since the new technology will be available sooner), but it also decreases the speed of adjustment (since fewer new firms enter and employment creation is sluggish). If the first effect dominates —and this is guaranteed if the time 0 level of employment is not too high—– high arrival time industries will also be low employment industries at T, and this results in the industry adopting the new technology faster and in higher levels of labor earnings (and market value) dispersion at the beginning of *Phase II*. The results are:

Proposition 8 *Given conditions* (A) *and* (B),
i) $\partial \hat{w}_1(\hat{y}, \mu)/\partial \mu = \partial \hat{w}_0(\hat{y}, \mu)/\partial \mu = 0, \partial \tilde{w}(\hat{y}, \mu)/\partial \mu < 0$,
ii) $\partial \hat{J}_1(\hat{y}, \mu)/\partial \mu = \partial \hat{J}_0(\hat{y}, \mu)/\partial \mu = 0, \partial \tilde{J}(\hat{y}, \mu)/\partial \mu < 0$,
iii)$\partial a_t(\hat{y}, \mu)/\partial \mu > 0$,
iv) $\partial \sigma_{wt}(\hat{y}, \mu)/\partial \mu \ (\partial \sigma_{Jt}(\hat{y}, \mu)/\partial \mu) \gtreqless 0 \Leftrightarrow a_t(\hat{y}, \mu) \lesseqgtr 1/2$.

Proof. See Appendix. ■

5 Some Evidence

In this section I briefly discuss some evidence. Given data limitations, most of the evidence comes from the "third" industrial revolution or the information technology (IT) revolution. Moreover, I emphasize the aggregate implications of the model. Sectoral differences are being studied as part of on-going research. Since the model is quite stylized, it is not reasonable to expect it to match perfectly all the aggregate data. With this caveat in mind, I find that the model does a reasonable job of explaining the behavior of some aggregate macro variables in the last 25 years.

In the following sections, I present data on the unemployment rate, the market value of business firms, levels of compensation and their variability, and investment ratios.

5.1 Unemployment Rates and the Stock Market

Consider first the relationship between the unemployment rate, the earnings-price ratio and the value of the a broad measure of the stock market value of firms, like the S&P 500 index. These three variables are displayed in Figure 4.

First, the predictions of the model capture the low frequency movements in the data. In order to make more precise statements, it is necessary to "date" phases I and II. Using the evidence in Figure 4, it seems that a reasonable choice for $t = 0$ (the beginning of *Phase I*) is sometime in the mid 1970s seventies, while $t = T$ is sometime in the mid eighties.

If *Phase I* is identified with the period starting in the mid 1970s the unemployment rate —as predicted by the model— increases until the mid 1980s. After that time unemployment decreases, which corresponds to the model's predictions for *Phase II*. As indicated, the model misses the increase in unemployment in the early nineties. The data also shows a decline in the value of business firms around 1974, and a recovery since the early to mid eighties. The main difference between the predictions of the model and the data is that, contrary to the theoretical predictions, the stock market declined gradually during the mid-seventies and early eighties. However, heterogeneity across sectors —as discussed in section 4— could account for smooth transitions. The increase in the earnings-price ratio predicted by the model appears in the data. During the ten year period from 1974 to 1984 (roughly *Phase I*) the earnings-price ratio was 10.92, while from 1960 to 1973 averaged 5.81, and from 1985 to 1997 it was 6.01.

As discussed before, the model also has predictions for the values of existing and new firms, and they seem to jive well with the available data. Greenwood and Jovanovic (1999) and Jovanovic and Hojbin (2000) argue that firms that were incumbents around 1970 fared a lot worse over the following 30 years than new entrants (in the stock market), and that a substantial part of the increase in the stock market value of all firms is due to the increase in the value of new entrants. Specifically, Jovanovic and Hojbin (2000) argue that relative to GDP the 1973 CRSP incumbents' value fell by more than 50% over a few years, and never fully recovered. The model has similar implications if we make the assumption that a "match" is a firm. In general, if some forms of organization capital are technology specific, we would expect that new firms would own a larger share of new technology matches than old firms. Thus, in this case, the qualitative predictions about matches would correspond to predictions about firms.

Jovanovic and Hojbin (2000) also show that the sectors that were more "informational technology intensive" (i.e. those that had made the largest investment in IT technologies) in 1996 also experienced the largest drop in market value in 1973.

The predictions about the behavior of the total value of firms relative to output also seem consistent with the data presented in Hall (2001): the value of this ratio is increasing until the early 70's; at that point it drops until the early to mid 80s. However, it is not only until the mid 90s that it gets back to the early 70s level. In terms of the model, this corresponds to z_t as defined in Proposition 6 which shows that the recovery —using this indicator— lags the increase in productivity.

5.2 Wage and Productivity: Levels and Dispersion

The model implies that, for each skill category, average compensation decreases around time 0, and, after a second decrease around time T, it starts to rise. In addition, it implies that within skill wage dispersion is associated with the technology that workers use.

Consider first the evolution of average compensation. Ideally, I would like to use data on full compensation for different skill levels and/or different sectors. However, a long time series with that level of disaggregation is not available. In Figure 5, I plot the deviations from trend of total real compensation per employee (in 1983 dollars). The pattern of the data broadly conforms to the model: real compensation is below trend in the mid-seventies, and it recovers in the mid-eighties. However, the model predicts that, around T, real wages should increase. In the data, real compensation remains below trend until the mid 1990s. Thus, relative to the evidence from the stock market and from unemployment data, the estimate of T is higher by about 7-8 years. Given the simplicity of the basic model without any kind of adjustment costs, this is not a bad approximation.

One common measure of dispersion is the standard deviation of the natural logarithm of real earnings. Using the March CPS data, Table 1 and Figures 6 and 7 document the changes in inequality since the early 1960s. The data show that there is an increase in dispersion in the 1980s and 1990s for most educational and experience categories. Thus, the overall increase in inequality between types of workers was accompanied by an increase in inequality within each education and/or experience category.

It is clear that there is an increase in the level of within group inequality, and that, for some categories, the increase exceeds that of the overall levels of inequality. The data are consistent with the view that more junior and more highly educated individuals —who are, presumably, more likely to be matched with new firms— display higher rates of increase in earnings dispersion. (See Table 1.)

Finding evidence of compensation dispersion is somewhat more difficult because of data availability. Dunne, Foster, Haltiwanger and Troske (2000) analyze hourly wage data and labor productivity data for the U.S. manufacturing sector during the period 1977-1992. As a measure of human capital they use production and non-production workers. Their evidence is strongly supportive of the model. They find that during the 1977-1992 period much of the increase in wage dispersion —measured by the coefficient of variation— is due to an increase in the between-plant dispersion within industries, with small changes in within-plant dispersion. During the period under study, the share of aggregate dispersion that is accounted for by between-plant differences in wages grows from 53% in 1977 to 64% in 1992.

Dunne, Foster, Haltiwanger and Troske (2000) also study the relationship between wages and productivity. For the U.S. manufacturing industry the cross sectional correlation between wages and productivity is quite high, varying between 0.52 and 0.57 for all years between 1975 and 1992. The correlation between plant level changes in productivity and wages is also positive for all subperiods. Finally, they examine cross industry differences in the changes in the between plant wage and productivity dispersion . They conclude that there is "compelling evidence that both cross-plant changes in wage and productivity dispersion are closely linked."

The timing of the changes is also roughly consistent with the simple model. Figure 2 of Dunne, Foster, Haltiwanger and Troske (2000) shows that, for the manufacturing sector, dispersion of log wages increases after 1982, and that, after a short-lived increase in 1983-84, between-plant dispersion of labor productivity also increases after 1986. Thus, in terms of the model discussed here, the increase in wage dispersion precedes, by about five years, the increase in productivity dispersion. It is possible that composition effects are influencing the aggregate, and more work on the timing of changes seems warranted.[9]

Bartel and Sicherman (1999) study a sample of young workers and conclude that the wage premium for an individual that is not due to either observed individual characteristics or industry affiliation is correlated with measures of technological change at the plant level. They interpret those results as evidence of sorting across industries on the basis of unobserved characteristics. Although this is a possible explanation, their evidence is also consistent with a model of no heterogeneity and mobility costs as the one in this paper, if their measures of technological change are correlated —as might be expected— with the fraction of plants that have upgraded their technology.

These figures are likely to underestimate the true increase in inequality in recent periods. Pierce (1999) uses the establishment survey micro data collected to produce the Employment Cost Index to argue that, in recent years, the increase in compensation inequality exceeds the increase in wage inequality. In his sample the 90-10 log wage difference from 1985-1987 to 1995-1997 increases from 1.521 to 1.550, while the same numbers for total compensation are 1.643 and 1.712. In the period 1982 - 1996, adding total compensation increases measured wage inequality by 14%.

5.3 Investment

The evolution of the non-residential investment output ratio for the U.S. economy during the 1966-1998 period reveals that during the mid-seventies investment decreases. However, by 1979 it has already recovered, and it peaks in 1981. Consistent with the model, the post 1983 period exhibits higher investment ratios. Thus, using the investment-output ratio to pin down the timing of the IT revolution, the results are still consistent with the view that $1974 = 0$. However, in this case, the onset of the new technology —a period that, according to the model, corresponds to higher investment— can be dated sometime in the late seventies. Relative to the conclusions derived from the unemployment rate, the market value of firms, and real wages, investment recovered faster (and more) than what is implied by the model.

The data on aggregate investment do not match well the notion of investment in the model. The latter considers only investment in new technologies, and it is not designed to capture all factors that affect investment. In this sense, it would be interesting to obtain data on investment by new plants or in new production lines, and compare it to the predictions of the theoretical model.

5.4 The Second Industrial Revolution

The adoption of the electric motor and the diffusion of other transportation and mass production technologies associated technologies at the turn of the 20th Century is another instance of a major technological innovation.

[9] These differences can be explained with a model in which the "best" technology is always improving. In such a model, the announcement in phase I slows down the adoption of new technologies and this, in turn, increases wage dispersion.

First, consider the "dynamo revolution." Even though electric power had been developed before 1890, it did not have a significant impact on productivity until the latter part of the 1910s. Using data from total factor productivity growth, David and Wright (1999) show that trend growth in the U.S. jumped from 1.5 percentage points per annum during 1899-1914 to 5.1 during 1919-1929. Even though less spectacular, the U.K. experience is similar, as it shows —with a delay relative to the U.S.— substantive increases in productivity associated with the adoption of electric motors during the 20s.

Several U.S. stock market indicators are consistent with the basic story of this paper. Jovanovic and Rousseau (2000) show that there is a substantial increase in entry of firms to the stock market during the 1915 and 1929. More relevant, they show that 1890 decade-vintage incumbents in the stock market —presumably users of the old technology— see their share of market capitalization decrease steadily during the during the 20s and 30s, while the 1920 decade-incumbents account for a large (and increasing) share of market capitalization during the same period.

Finally, real manufacturing wages in the U.S. were stagnant in 1890-1920 period, only to see an increase of close to 70% during the 20s.

Thus the limited aggregate evidence from productivity growth, the stock and the labor market suggest that the broad patterns of the last 30 years agree with those of the first 30 years of the 20th century.

During the first decades of the 20th century the U.S. agricultural sector slowly adopted a new major technology: it substituted tractors for draft horses. Even though early tractors were not perfect substitutes for horses, a recent study by Olmstead and Rhode (2000) show that, from 1910 to 1920, the real price of tractors decreased approximately 60%. During the same period, the real price of draft horses —the "old technology"— also decreased by 60%, even though in 1920 only 3.6% of all U.S. farms had a tractor (see Figure 3 in Olmstead and Rhode (2000)). Thus, even before the tractor had diffused, the introduction of a new technology had the effects of lowering the market value of the existing technology. Thus, at least for the "tractor revolution," anticipation effects mattered.

6 Extensions and Conclusions

In order to highlight the effects of anticipated technological advances, the model was kept deliberately simple. Even the analysis of heterogeneity was restricted to the major driving force: technological change. In some sense, adapting the model so that it can confront micro observations about workers-plant data will require extensions to account for heterogeneity in productivity and ability to adapt to new technologies. With heterogeneous firms, the model will predict flows of job creation and destruction associated with new technologies, as well as the link between adoption, earnings inequality and dispersion in market values. Finally, expanding section 4, different sectors are probably affected very differently by a major innovation such as the IT revolution.

The major emphasis of the paper is to show that the anticipation of the arrival of a more productive technology delays investment decisions. The expectation of lower future profits by firms that have to purchase the current, soon to be obsolete, technology drives their market value, and the wages they pay, down. The decrease in market value without changes in productivity result in an increase in the earnings-price ratio.

When the technology finally becomes available (i.e. it is mature), it is gradually adopted by new firms. This corresponds to a period of high investment, increasing wages and higher wage dispersion among identical workers. The increase in dispersion is due to a friction in the labor market: workers matched with the new technology receive higher wages, and even though workers operating the old technology also enjoy a wage increase, their wages fall short of those received by workers matched with the new technology. Since, over time, all firms adopt the new technology, the model implies that technological revolutions cause a *temporary* increase in inequality.

Sectors that benefit from the largest productivity increases also suffer the most during the pre-adoption period: the market value of firms in those sectors decreases more than the average, and labor earnings also fall be more than the average. When the technology becomes available these sectors adopt at a faster rate, and display higher dispersion of both labor earnings and the market value of firms.

The model is consistent with some observations on the U.S. economy corresponding to the IT revolution. In particular, it suggests that, in addition to other macro shocks, the increase in unemployment, the drop in the market value of firms and in real wages in the mid seventies could be due to the recognition that the technologies soon to be available would render existing firms technologically (or organizationally) obsolete. The model indicates that the increase in productivity, that starts sometime in the eighties, could be understood as the beginning of the period in which the new IT technologies finally matured.

Finally, the model argues that developments in the stock and labor market were driven by the same forces: anticipation of future higher productivity. The model shows how "good news" can result in poor performance of the economy in the short run, in the absence of any costs of adjustment, and it emphasizes that sectors that get "hit" by better shocks show the weakest performance before the technology arrives and display the fastest rate of adoption and higher levels of dispersion after the technology becomes available.

References

[1] Acemoglu, D, (1998a), "Why do New Technologies Complement Skills? Directed Technical Change and Wage Inequality," *Quarterly Journal of Economics*, Vol. 113, pp: 1055-1089.

[2] Acemoglu, D, (1998b), "Changes in Unemployment and Wage Inequality: An Alternative Theory and Some Evidence," *American Economic Review*, Vol. 89, pp: 1259-1278.

[3] Acemoglu, D, (2000), "Technical Change, Inequality, and the Labor Market," NBER Working Paper No. 7800, July.

[4] Acemoglu, D. and R. Shimer, (2000), "Wage and Technology Dispersion," *Review of Economic Studies*, forthcoming.

[5] Atkeson, A. and P. Kehoe, (2000), "Industry Evolution and Transition: A Neoclassical Benchmark," NBER working paper No. 6005, April.

[6] Bartel, A. P. and N. Sicherman, (1999), "Technological Change and Wages: An Interindustry Analysis," *Journal of Political Economy*, Vol. 107, No. 2, pp: 285-325.

[7] Card, D. and T. Lemieux, (1996), "Wage Dispersion, Returns to Skill, and Black-White Wage Differentials, *Journal of Econometrics*, Vol 74, No 2, pp: 319-361, October.

[8] Caselli, F., (1999), "Technological Revolutions," *American Economic Review*, Vol. 89, No 1, pp: 78-102, (March).

[9] Davis, S. J. and J. Haltiwanger, (1991), "Wage Dispersion Between and Within U.S. Manufacturing Plants," *Brookings Papers on Economic Activity: Microeconomics 1991*, pp: 115-180.

[10] Davis, S., J. Haltiwanger, and S. Schuh, (1996), *Job Creation and Job Destruction*, MIT Press, Cambridge, London.

[11] David, P. A. and G. Wright, (1999), "General Purpose Technologies and Surges in Productivity: Historical Reflections on the Future of the ICT Revolution," Stanford University Working Paper.

[12] Dunne, T, L. Foster, J. Haltiwanger, and K. Troske, (2000), "Wage and Productivity Dispersion in U.S. Manufacturing: The Role of Computer Investment," NBER Working Paper 7465, January.

[13] Estevão, M. and S. Tevlin, (2000), "Do Firms Share their Success with Workers? The Response of Wages to Product Market Conditions," Federal Reserve Board, Finance and Economics Discussion Paper 2000-17, March.

[14] Eriksson, T and M. Jntti, (1997), "The Distribution of Earnings in Finland," *European Economic Review*, No. 41, pp: 1763-1779.

[15] Foote, C., (1998), “Trend Employment Growth and the Bunching of Job Creation and Job Destruction,” working paper, Harvard University, January.

[16] Greenwood, J and M. Yarakoglu, (1997), “1974,” *Carnegie-Rochester Conference Series on Public Policy*,

[17] Greenwood, J. (1997), “The Third Industrial Revolution: Technology, Productivity and Income Inequality,” *AEI Studies on Understanding Inequality*, Washington, DC. The AEI Press. Also, reprinted in the *Economic Review*, 1999, Federal Reserve Bank of Cleveland.

[18] Greenwood, J. and B. Jovanovic, (1999), “The IT Revolution and the Stock Market.” *AEA Papers and Proceedings*, May.

[19] Gort, M. and S. Klepper, (1982), “Time Paths in the Diffusion of Product Innovations,” *Economic Journal*, Vol. 92, No. 367, pp: 630 - 653, September.

[20] Hall, Robert E., (2001), “Struggling to Understand the Stock Market: The 2001 Ely Lecture,” Stanford University working paper.

[21] Hoxby, C. M. and B. Terry, (1999), “Explaining Rising Income and Wage Inequality Among the College-Educated,” NBER working paper No. 6873, January.

[22] Jovanovic, B., (1998), “Vintage Capital and Inequality,” *Review of Economic Dynamics*, Vol. 1, No. 2, pp: 497-530, April.

[23] Jovanovic, B. and B. Hobijn, (2000), “The IT Revolution and the Stock Market: Evidence,” NYU working paper.

[24] Jovanovic, B. and S. Lach, (1997), “Product Innovation and the Business Cycle,” *International Economic Review*, Vol. 38, No. 1, pp: 3-22, February

[25] Jovanovic, B. and R. Rob, (1999), “Solow vs Solow,” working paper.

[26] Jovanovic, B. and P. L. Rousseau, (2000), “Technology and the Stock Market: 1885-1998,” working paper.

[27] Mortensen, D. and C. Pissarides, (1994), “Job Creation and Job Destruction in the Theory of Unemployment,” *Review of Economic Studies*, 61, 397-415.

[28] Olmstead, A. and P. Rhode, (2000), “The Diffusion of the Tractor in American Agriculture: 1910-1960,” NBER Working Paper 7947, October.

[29] Pierce, B., (1999), “Compensation Inequality,” BLS Working Paper Number 323, U.S. Department of Labor, June.

A Appendix

Proof of Proposition 3. To prove i) it suffices to show that the surplus associated with continuing the match using the "old" technology,$\hat{S}_0$, is non-negative. Given

$$\begin{aligned} r\hat{J}_0 &= y^* - \hat{w}_0 + \eta(\hat{V} - \hat{J}_0 - k), \\ r\hat{E}_0 &= \hat{w}_0 + \eta(\hat{U} - \hat{E}_0), \\ r\hat{U} &= z + \hat{\theta}q(\hat{\theta})(\hat{E}_1 - \hat{U}), \end{aligned}$$

it follows that

$$\begin{aligned} (r+\eta)(\hat{E}_0 - \hat{U}) &= \hat{w}_0 - r\hat{U}, \\ (r+\eta)\hat{J}_0 &= y^* - \hat{w}_0. \end{aligned}$$

Thus,

$$(r+\eta)\hat{S}_0 = y^* - r\hat{U}.$$

Since a similar calculation establishes that $(r+\eta)\hat{S}_1 = \hat{y} - r\hat{U}$, it follows that

$$(r+\eta)\hat{S}_0 = (r+\eta)\hat{S}_1 - (\hat{y} - y^*).$$

Thus, $\hat{S}_0 \geq 0$ if and only if $(r+\eta)\hat{S}_1 - (\hat{y} - y^*) \geq 0$. Since in equilibrium $\hat{J}_1 = (1-\phi)\hat{S}_1$, (16) implies that the necessary and sufficient condition is

$$\frac{r + q(\hat{\theta})}{q(\hat{\theta})} \geq (1-\phi)\frac{(\hat{y} - y^*)}{r+\eta},$$

which is just Condition B.

ii) From the Nash bargaining condition it follows that

$$(r+\eta)(\hat{E}_0 - \hat{U}) = \frac{\phi}{1-\phi}(r+\eta)\hat{J}_0,$$

which, using the previous calculations implies

$$\hat{w}_0 = \phi y^* + (1-\phi)r\hat{U}.$$

Since the same argument shows that

$$\hat{w}_1 = \phi\hat{y} + (1-\phi)r\hat{U},$$

it follows that

$$\hat{w}_0 = \hat{w}_1 - \phi(\hat{y} - y^*).$$

iii) Given that $\hat{w}_0 = \hat{w}_1 - \phi(\hat{y} - y^*)$, and (9) we get that

$$\hat{w}_0 = z + \phi[y^* - z + \hat{\theta}(r + q(\hat{\theta}))k].$$

Since w^* is given by the appropriate version of (9), it follows that

$$\hat{w}_0 \geq w^* \quad \leftrightarrow \quad \hat{\theta}(r + q(\hat{\theta})) \geq \theta^*(r + q(\theta^*)),$$

which is satisfied since $\theta(r + q(\theta))$ is increasing in θ and $\hat{\theta} > \theta^*$. ■

Proof of Proposition 4. Given that the right hand side of (19) is an increasing function of θ, it suffices to show that $\theta^* \geq \tilde{\theta}$. Note that (17) for any given θ is

$$\tilde{w} = y^* - (r+\eta)\frac{(r + q(\theta))k}{q(\theta)} + \mu(\frac{(r + q(\hat{\theta}))k}{q(\hat{\theta})} - (1-\phi)\frac{\hat{y} - y^*}{r + \eta} - \frac{(r + q(\theta))k}{q(\theta)}) \equiv m_1(\theta),$$

where I used the fact that $\hat{J}_0 = \hat{J}_1 - (1 - \phi)\frac{\hat{y}-y^*}{r+\eta}$. Since in equilibrium (19) must hold, let its right hand side be denoted $m_2(\theta)$. Thus,

$$m_2(\theta) \equiv z + \phi(y^* - z + \theta(r + q(\theta))k).$$

The intersection between $m_1(\theta)$ and $m_2(\theta)$ determine the equilibrium $(\tilde{w}, \tilde{\theta})$. Since $m_2(\theta)$ is increasing and $m_1(\theta)$ is decreasing it suffices to show that $m_2(\theta^*) > m_1(\theta^*)$. At $\theta = \theta^*$we obtain

$$\begin{aligned} m_1(\theta^*) &= m_2(\theta^*) + \mu(\frac{(r + q(\hat{\theta}))k}{q(\hat{\theta})} - (1 - \phi)\frac{\hat{y} - y^*}{r + \eta} - \frac{(r + q(\theta^*))k}{q(\theta^*)}) \\ &= m_2(\theta^*) + \mu(f(\hat{y}) - f(y^*)), \end{aligned}$$

where

$$f(y) = \frac{rk}{q(\theta(y))} - (1 - \phi)\frac{y}{r + \eta},$$

and $\theta(y)$ is the unique value of θ that solves (6) and (9). If we can show that $f(y)$ is a decreasing function of y we obtain $m_2(\theta^*) > m_1(\theta^*)$ as needed. From (6) and (9) it follows that

$$f(y) = -k - \frac{z(1 - \phi)}{r + \eta} - \frac{\theta(y)(r + q(\theta(y))k}{r + \eta}.$$

Since $\theta(y)$ is increasing in y, the result follows. Finally to complete the argument I show that $m_2(0) < m_1(0)$. This is equivalent to

$$(1 - \phi)(y^* - z) - (r + \eta)k + \mu[\frac{rk}{q(\hat{\theta})} - (1 - \phi)\frac{\hat{y} - y^*}{r + \eta}] > 0,$$

which is satisfied given Assumptions A and B. ■

Proof of Proposition 5. Since $J = (1 - \phi)S$, and —as shown in the proof of Proposition 4 $\hat{S}_0 < \hat{S}_1$— it follows that $\hat{J}_0 < \hat{J}_1$. Given that free entry implies that $J = k + rk/q(\theta)$, and since it was shown that $\tilde{\theta} < \theta^* < \hat{\theta}$, it follows that $\tilde{J} < J^* < \hat{J}_1$. To complete the proof it is necessary to show that $\hat{J}_0 < \tilde{J}$. From the Bellman equation corresponding to $\hat{J}_0$ and $\tilde{J}$ it follows that

$$\tilde{J} - \hat{J}_0 = \frac{\hat{w}_0 - \tilde{w}}{r + \eta + \mu}.$$

Given that $\hat{w}_0 = \hat{w}_1 - \phi(\hat{y} - y^*)$ and using (9) to eliminate $\hat{w}_1$, we obtain

$$\hat{w}_0 = z + \phi[y^* - z + \hat{\theta}(r + q(\hat{\theta}))k],$$

while (9) implies that $\tilde{w}$ is

$$\tilde{w} = z + \phi[y^* - z + \tilde{\theta}(r + q(\tilde{\theta}))k].$$

Thus,

$$\tilde{J} - \hat{J}_0 = \frac{\phi k[\hat{\theta}(r + q(\hat{\theta})) - \tilde{\theta}(r + q(\tilde{\theta}))]}{r + \eta + \mu}$$

which is positive since $\hat{\theta} > \tilde{\theta}$. ■

Proof of Proposition 6. Omitted. It is a simple calculation. ■

Proof of Proposition 7. i) Since $\hat{\theta}$ is an increasing function of $\hat{y}$ (see (6) and (9)) it follows that $\hat{w}_1$ increases with $\hat{y}$ (see (9)). Since —as derived in the proof of Proposition 5—

$$\hat{w}_0 = z + \phi[y^* - z + \hat{\theta}(r + q(\hat{\theta}))k],$$

it follows that increases in $\hat{y}$ increase $\hat{w}_0$. To determine the the impact of an increase in $\hat{y}$ on $\tilde{w}$ it suffices to calculate its effect on $\tilde{\theta}$ given that

$$\tilde{w} = z + \phi[y^* - z + \tilde{\theta}(r + q(\tilde{\theta}))k].$$

In the proof of Proposition 4 it was shown that $\tilde{\theta}$ is the solution to the equation $m_1(\theta) = m_2(\theta)$. Since $m_2(\theta)$ — which is upward sloping— does not depend on $\hat{y}$, and

$$m_1(\theta) = y^* - (r + \eta)\frac{(r + q(\theta))k}{q(\theta)} + \mu(f(\hat{y}) + (1 - \phi)\frac{y^*}{r + \eta} - \frac{(r + q(\theta))k}{q(\theta)})$$

with $f(\hat{y})$ decreasing in $\hat{y}$, it follows that $\tilde{\theta}$ decreases as a result of increases in $\hat{y}$.

ii) Since $\hat{J}_1 = k + rk/q(\hat{\theta})$, it follows that $\hat{J}_1$ is increasing in $\hat{y}$. In the proof of Proposition 3 it was shown that

$$(r + \eta)\hat{S}_0 = (r + \eta)\hat{S}_1 - (\hat{y} - y^*),$$

which implies that

$$\hat{J}_0 = \hat{J}_1 - (1 - \phi)\frac{\hat{y}}{r + \eta} = f(\hat{y}) + k,$$

which is decreasing in $\hat{y}$. Finally, since $\tilde{J} = k + rk/q(\tilde{\theta})$ and $\tilde{\theta}$ decreases with $\hat{y}$, the result follows.

iii) First consider the effect of $\hat{y}$ on n_T, the level of employment at the time in which the technology becomes available. Using the law of motion for unemployment during *Phase I*, it is easy to verify that n_T is given by,

$$n_T = \tilde{n} + (n_0 - \tilde{n})e^{(\eta + \hat{\theta}q(\hat{\theta}))T},$$

where $\tilde{n} = \tilde{\theta}q(\tilde{\theta})/[\eta + \tilde{\theta}q(\tilde{\theta})]$. Differentiation of the expression for n_T shows that a sufficient condition for $\partial n_T/\partial \hat{y} \leq 0$ is that

$$n_0 \leq \tilde{n} + (1 - \tilde{n})\frac{e^{(\eta+\hat{\theta}q(\hat{\theta}))T} - 1}{(\eta+\hat{\theta}q(\hat{\theta}))T}$$

or, since $n_0 \leq 1$,

$$1 - \tilde{n} \leq (1 - \tilde{n})\frac{e^{(\eta+\hat{\theta}q(\hat{\theta}))T}}{(\eta+\hat{\theta}q(\hat{\theta}))T}$$

which is satisfied as $e^v \geq 1 + v$, for all $v \geq 0$. Moreover, since $\partial n_T/\partial \hat{y} \leq 0$ implies $\partial \pi_t/\partial \hat{y} \leq 0$, it follows that $\partial a_t/\partial \hat{y} \geq 0$.

iv) From (22) it follows that

$$\frac{\partial \sigma_{w,t}}{\partial \hat{y}} = \phi[(\pi_t(1 - \pi_t))^{1/2} + (\hat{y} - y^*)(\pi_t(1 - \pi_t))^{-1/2}(1 - 2\pi_t)\frac{\partial \pi_t}{\partial \hat{y}}]$$

which is non-negative provided that $1 - 2\pi_t \leq 0$ ($a_t \leq 1/2$) since $\partial \pi_t/\partial \hat{y} \leq 0$. This completes the proof. ■

Proof of Proposition 8. Omitted as it parallels the proof of Proposition 7 with μ taking the place of $\hat{y}$ ■

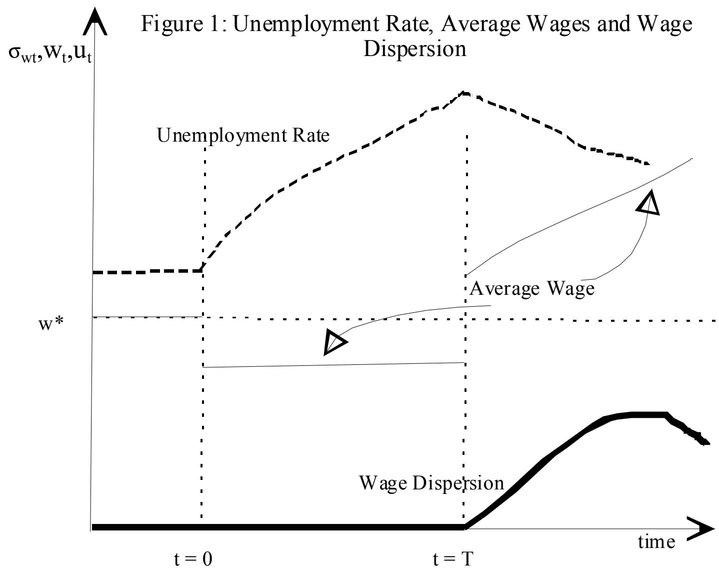


Figure 1: Unemployment Rate, Average Wages and Wage Dispersion
σ_{wt}, w_t, u_t
Unemployment Rate
Average Wage
w*
Wage Dispersion
time
t = 0
t = T

Figure 1:

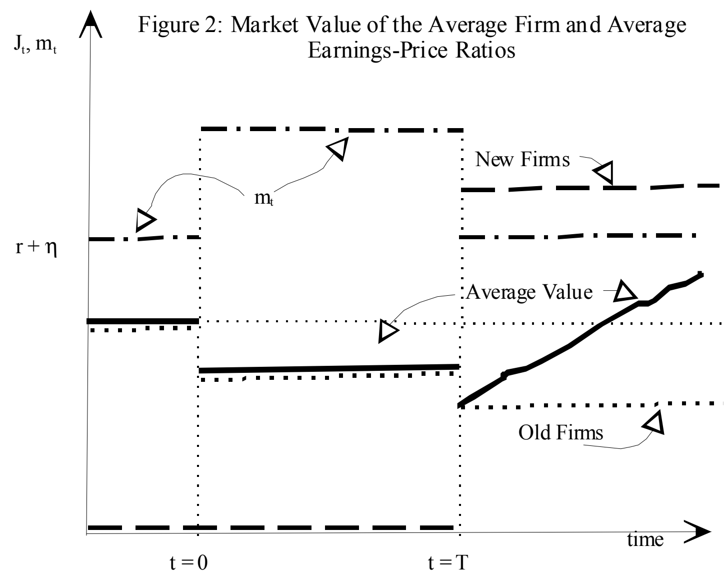


Figure 2: Market Value of the Average Firm and Average Earnings-Price Ratios
J_t, m_t
$r + \eta$
m_t
New Firms
Average Value
Old Firms
time
t = 0
t = T

Figure 2:

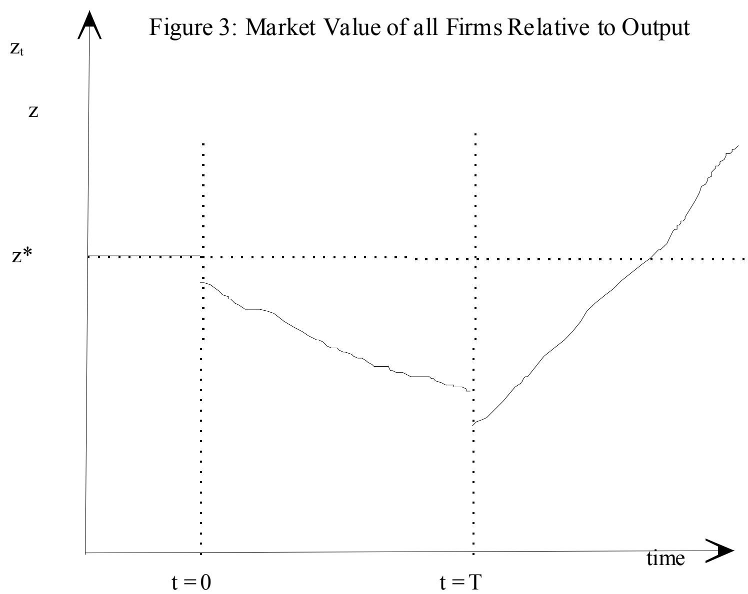
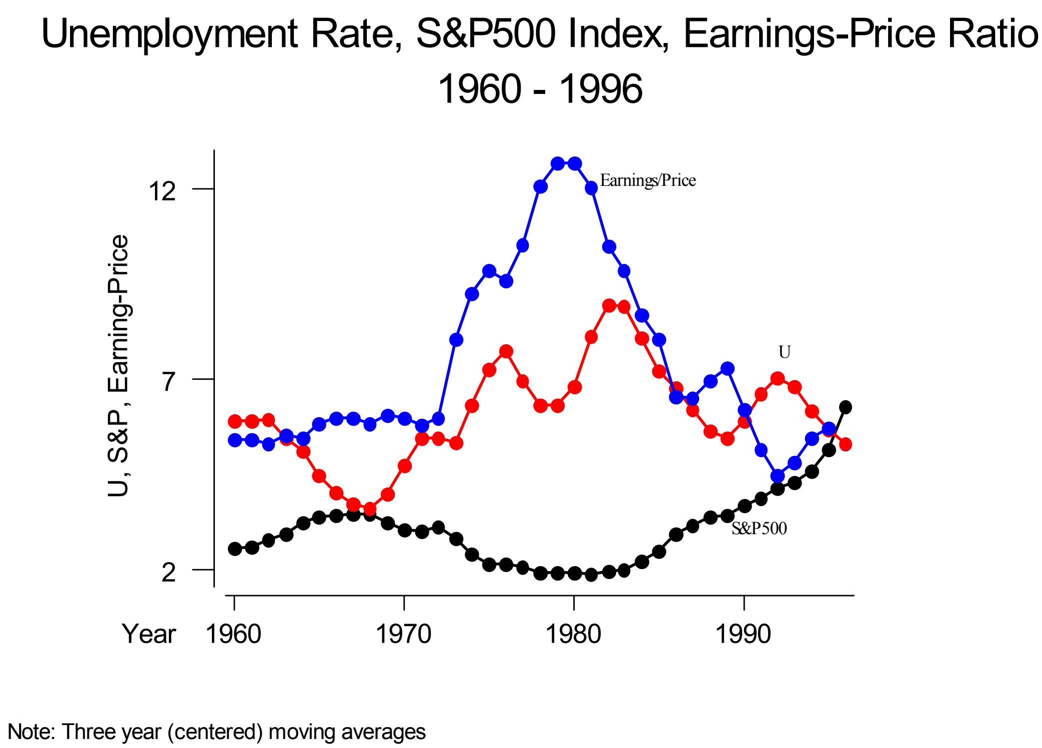


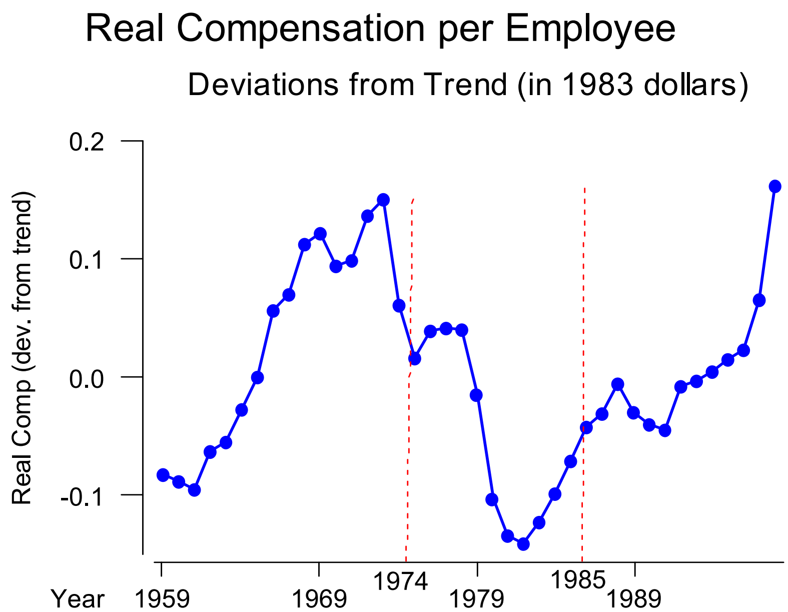
Figure 3: Market Value of all Firms Relative to Output
z_t
z
z*
time
t = 0
t = T

Figure 3:



Unemployment Rate, S&P500 Index, Earnings-Price Ratio
1960 - 1996
U, S&P, Earning-Price
12
7
2
Earnings/Price
U
S&P500
Year
1960
1970
1980
1990
Note: Three year (centered) moving averages

Figure 4:



Note: Residuals from regressing real compensation per employee
(Economic Report of the President) on a second order polinomial in time

Figure 5:

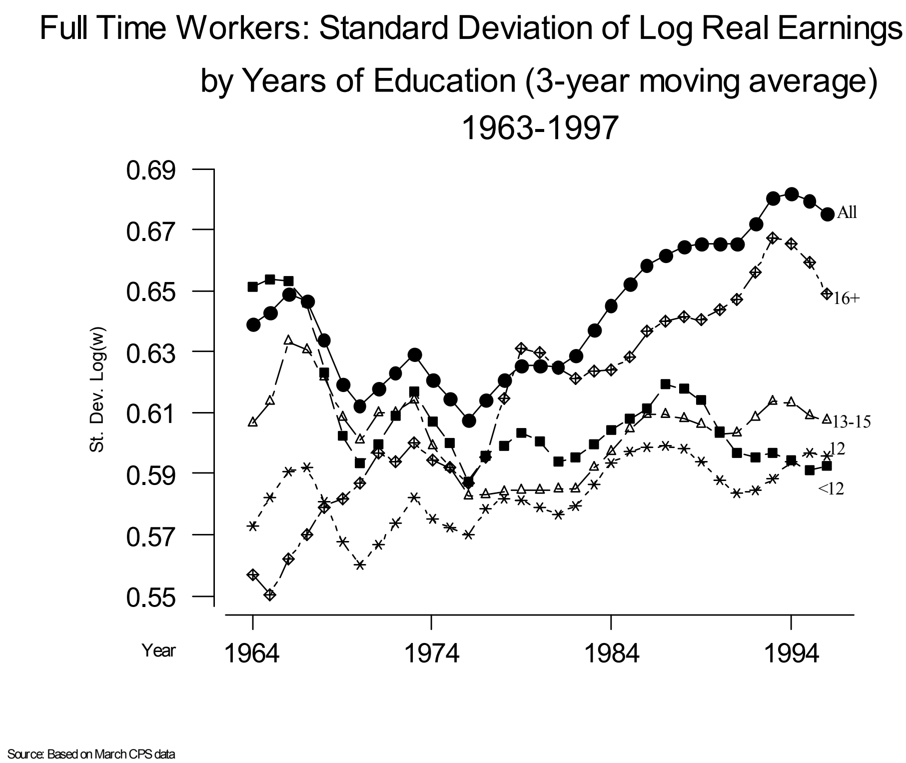
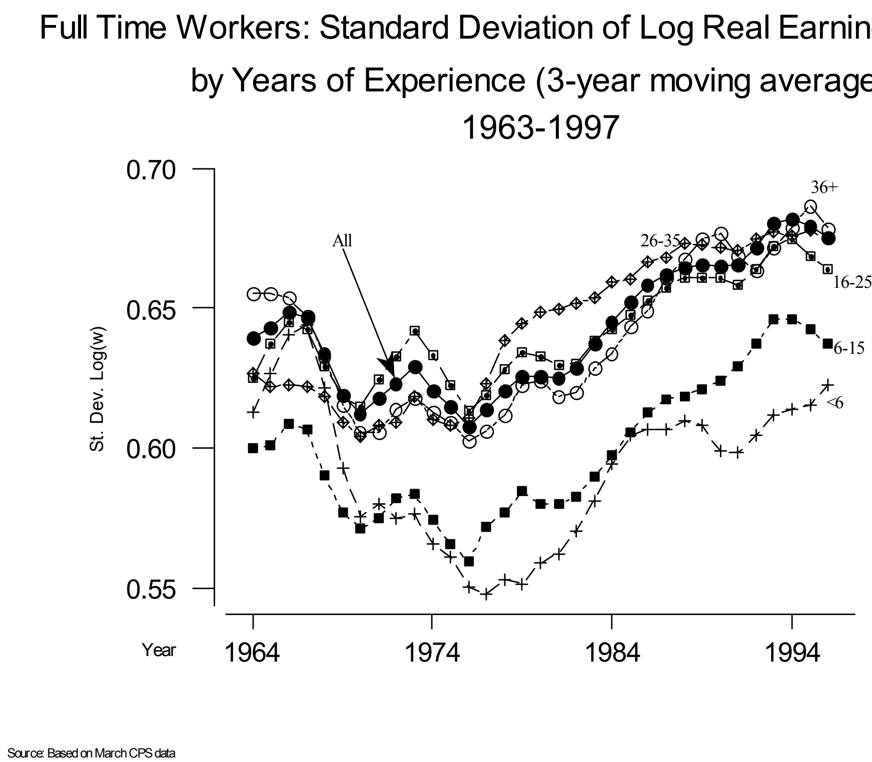

Full Time Workers: Standard Deviation of Log Real Earnings
by Years of Education (3-year moving average)
1963-1997
0.69
0.67
0.65
0.63
0.61
0.59
0.57
0.55
St. Dev. Log(w)
Year
1964
1974
1984
1994
All
16+
13-15
12
<12
Source: Based on March CPS data

Figure 6:



Full Time Workers: Standard Deviation of Log Real Earnings
by Years of Experience (3-year moving average)
1963-1997
0.70
0.65
0.60
0.55
St. Dev. Log(w)
Year
1964
1974
1984
1994
All
26-35
36+
16-25
6-15
<6
Source: Based on March CPS data

Figure 7:

Concept	σ_{70}	σ_{80}/σ_{70}	σ_{90}/σ_{70}
All	0.62	1.05	1.08
Education			
College +	0.60	1.05	1.10
Some College	0.60	1.00	1.02
High School	0.57	1.04	1.04
High School -	0.60	1.02	1.02
Experience			
Less than 6	0.56	1.05	1.09
6-15	0.57	1.05	1.12
16-25	0.63	1.03	1.06
26-35	0.62	1.06	1.08
36+	0.61	1.05	1.10
College +			
6-15	0.52	1.08	1.15
26-35	0.63	1.09	1.08
Some College			
6-15	0.49	1.06	1.08
26-35	0.59	1.02	1.00
High School			
6-15	0.52	1.04	1.04
26-35	0.56	1.04	1.04

Table 1: Standard Deviation of Log Real Earnings: Various Categories (by decade)

Sample Selection: Real weekly earnings for full time ("usually worked 35+ hours per week") workers age 18-65, who worked no less than 14 weeks. Excluded were: all individuals with imputed wage and salary income for the survey years 1968-1998; all individuals with imputed total income for the survey years 1964-1967; self-employed workers (those with positive self-employment income and those with negative self-employment income exceeding $200 in 1996 dollars); individuals earning less than $17 week (1982 dollars), which corresponds to 1/2 the minimum wage for a 10 hour week.