# Contracting Productivity Growth*

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**Abstract**

In this paper, we analyze the interactions between growth and the contracting environment in the production sector. Allowing incompleteness in contracting implies that viable production relationships for firms and workers, and therefore the profitability of industries, depend on the rates of innovation and growth. The speed at which new innovations arrive in turn depends on the profitability of production, for the usual reasons examined in the endogenous growth literature. We show that these interactions can have important implications which are consistent with observed phenomena in both the micro and macro environment. In particular, we demonstrate that a technological shock (increasing productivity of research) can, through this interaction, lead to a productivity slowdown and a shift in labour market contracts toward more short term arrangements. We show the consistency of an increase in the proportion of the labour force under short term employment, unchanged turnover, increased relative returns of workers in high productivity sectors, and increased income inequality, with a productivity slowdown of finite duration.

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# 1 Introduction

Though difficult to date precisely, the early 1970s seemed to herald three major waves of change in the US macroeconomy. These were: (1) the IT revolution, (2) the productivity slowdown and (3) the commencement of the erosion of internal labor markets.[1] This paper demonstrates a link between all three. The starting point for our analysis is recognition of the fact that the set of feasible contracting relationships between workers and firms is constrained by the macroeconomy, while simultaneously macroeconomic variables are affected by microeconomic incentives.

Specifically, we consider an environment where firms and workers cannot explicitly contract over worker effort in production, and analyze the form of "relational contracts" in their repeated interaction that will support a productive relationship.[2] One possible form of relational contract is for the firm to reward workers with delayed benefits that are paid only once the worker's effort is ascertained by the firm. We refer to such a relational contract as an "internal labor market" and its existence depends critically on the firm's valuation of its reputation. This, however, depends on the firm's expected life-time. In an environment with high potential growth and rapid firm turnover, firms cannot make credible promises of delayed reward to workers, so the internal labor market is necessarily limited. This is the sense in which the macroeconomy constrains feasible micro level contracts. On the other hand, incentives to innovate, and hence the economy's growth rate, depend on returns in production, which are lower when labour costs are high, that is, when the internal labor market is limited. Thus, micro level contracting relationships also affect the macro environment. We show here that these interrelationships can explain the US economy's behaviour along the three dimensions above.

Put simply, our story is as follows. The information technology (IT) revolution heralded a period of high productivity of inventive effort.[3] In addition to its productivity, however, returns to inventive effort depend on the degree to which successes can be profited from. This, in turn depends on the form of contracting relationship between firms and employees. Since employees will have to be hired to use the new technologies that are developed. Prior to the slowdown, these contracting relationships could best be characterized as an internal labor market; firms rewarded workers with deferred benefits and were themselves disciplined to provide these rewards by their own reputation in the labor market. The increased innovative potential accompanying the IT revolution implied more rapid turnover in best-practice productive arrangements. These eventually reached a point (which may have differed by sector) where firms' labor market reputations provided insufficient discipline for the maintenance of the internal labor market. Thus, while the

[1] We review the evidence in support of these assertions in the next section.

[2] The term "relational contract" has been used by Baker Gibbons and Murphy (1997) to denote these sorts of implicit contracts, a special case of these have also been called "efficiency wage" contracts. These are discussed, and the related literature reviewed in Malcomson (1999).

[3] Greenwood and Jovanovic (1999) date the IT revolution to the early 1970's.

IT revolution began working its way through the economy, within industry labor markets underwent a fundamental change from being internal labor markets to what we term "contractor" based labor markets. We present the evidence for the increase in such labor markets in the next section. In a contractor labor market, the moral hazard is not borne by the employer but by labor, who are disciplined by their own reputations to provide correct effort. This leads to a shift in the distribution of returns away from firms towards labor since, as has already been realized in the theoretical literature, see Macleod and Malcomson (1989), incentive compatibility requires that the party standing to gain from opportunistic behavior must receive a surplus to continued honest participation. Each industry where the labor market undergoes such a restructuring thus experiences an industry wide decline in returns to innovation which offsets the potential productivity gains from the IT revolution. Thus, over this phase, the induced changes in the labor market heralded in by the IT revolution lead to the seemingly paradoxical possibility of lower productivity growth while the raw productivity of labor in research rose.[4]

Part of this paper's aim is more theoretical in focus. A major contribution of the recent technology based branch of the endogenous growth literature is its incorporation of plausible microeconomic foundations for innovation as a determinant of growth. For reasons of tractability, this literature has abstracted from many microeconomic complexities. In particular, in the labor market, an obvious abstraction is the implicit assumption of completeness in contracting relations between workers and firms, which allows workers to be rewarded with a market clearing competitive wage. This contrasts with the more careful modelling of production relationships in both industrial organization and labor economics, where production under incomplete contracting has been more thoroughly examined.[5] Here, we allow for such incompleteness in contracting.

Formally, we augment a standard Schumpeterian growth model, as in Grossman and Helpman (1991) and Aghion and Howitt (1992), with incomplete contracting in production. We exclude the possibility of legally enforceable payments for worker effort, and consider only those effort/wage pairs that are self-enforcing. It has been widely argued that the non-verifiable particulars of a worker/firm relationship do not allow for explicit contracting over payments that are contingent upon worker performance (see Macleod and Malcomson 1989). In such a framework, only self-enforcing payments and effort will be supplied in equilibrium. With sufficient surplus to production arrangements, however, it is well known that a multiplicity of self-enforcing wage/effort pairs is possible. It is in the creation of a surplus that innovation affects contracting. In an endogenous growth context, the surpluses required to sustain production arise naturally as the rewards to successful innovative activity. Thus, in our environment, monopoly profits to innovation serve two roles: in addition to the standard role of providing incentives for innovation they

[4]Information possessing capacity, or the IT revolution can be thought of as a general purpose technology, which is how we model it. However nothing in the model requires that it be 'general' in fact the results will obtain if different sectors are affected to differing degrees.

[5]For surveys, see Hart (1995), Gibbons (1997) and Malcomson (1999).

serve to provide sufficient surplus so that performance contingent implicit contracts can be self enforcing.

There is already a large literature exploring the macroeconomic implications of microeconomic models of the employment relationship, in particular with respect to aggregate employment levels, (Macleod, Malcomson and Gomme 1994 and Shapiro and Stiglitz 1984), and job destruction over the cycle; (Ramey and Watson 1997, Caballero and Hammour 1996). A closer precursor of this work is Aghion and Howitt (1994) which explores causation from growth rates to unemployment through the destructive effects of new knowledge on existing job matches. At a theoretical level, Ramey and Watson (1997) also related the feasibility of the incomplete contracting relationship and its vulnerability to aggregate downturns. A major difference is that their work is concerned with cyclical aspects of this relationship and they do not explore the reverse direction of effect of micro contracting on the macroeconomy. The present paper is the first, to our knowledge, to explore the effects of the macro environment (in particular the innovation arrival, and hence growth, rate) on the possibility for contracting at the micro level, and also to explore the reverse causation of contracting at the micro level's effects on growth.

The explanation arising from our model resembles previous attempts to explain the slowdown by labor market induced changes in innovation, or dissemination and implementation of new technology, i.e., Hornstein and Krusell (1996), Greenwood and Yorukoglu (1997) and Lloyd-Ellis (1999). Since these approaches do not including a role for contracting at the micro level, they are clearly structurally very different to the one we present. However, since they essentially attempt to explain a similar set of phenomena, we leave to a later section discussion of the precise distinction between our analysis and these in terms of predictions. Before developing our story more formally however, we provide a brief overview of the facts motivating our analysis.

## 1.1 Changes in the macro and micro environment over the 70's and 80's

### 1.1.1 The productivity slowdown:

Since the early 1970s there has been a secular decline in the rate of productivity growth (both labor and total factor) in many western developed economies. Focusing on the US, from a trend rate of approximately 2.2% from 1950-1972, the rate of labor productivity growth (excluding agriculture) declined to about 1% from 1972 to 1987 and 1.2% from 1987 to 1994. There has been some debate as to the reliability of measures of productivity growth. Krussell and Hornstein (1996) argue that the slowdown is overstated due to mismeasurement of the new, and hence most rapidly growing, sectors, see also Grilliches (1994) and Sichel (1997) on this. However, Gordon (1996) accounts for these measurement errors and shows that, though these have severely biased sectoral measures of productivity, they imply, if anything, an increase and persistence in the level of the slowdown at an aggregate level. More recently, Dolmas, Raj and Slottje (1999) present formal statistical evidence that the log level of productivity underwent a change in both level and slope of its linear trend in the 1970s. Over the late 1990's growth in labour productivity has increased once again, from 1995-1999 output per hour in non-farm business grew at an average annual rate of 2.5%, see Oliner and Sichel (2000).

### 1.1.2 Research and Development:

In face of the decline in productivity growth, the level of resources devoted to research and development do not appear to have diminished over the corresponding period. In fact, the evidence suggests that the number of researchers in both the US and G-5 economies has increased steadily throughout the 1970s and 1980s, see Jones (1998). In absolute numbers, this has been clearly the case in all of these economies; proportionately, this has also been true, except for the early part of the 1970s in the US.

### 1.1.3 The labor market:

*The rise of contract work.* There has been a large increase in the number of contingent workers, or those working without an expectation of ongoing employment. Recent estimates put the numbers in such positions at 12 million workers or over 10% of the US labor force, see Cohany (1996).

Early accounts of this phenomenon tended to treat these individuals as a homogeneous group, but it is important to distinguish at least two distinct types of contingent workers. At one end of this group are "temp" workers. These are workers filling relatively low paid jobs with low skills, little opportunity for advance and low job satisfaction. It appears that the rise in their numbers has been motivated largely by cost reducing considerations on the part of employers, see Abraham (1990, p. 102), and therefore that these changes are not directly related to the considerations at the heart of this paper. Despite the large amount of media attention these individuals have received, they do not make up the bulk of the contingently employed. Approximately 8.3 million of the 12 million workers in non-traditional arrangements are independent contractors, 75% of whom work alone. There is no evidence that the increase in their numbers is attributable to employers cutting costs; rates of pay for independent contractors in business service firms are comparable to or higher than rates of pay to the permanent employees, (Abraham 1990, p. 102). These are generally relatively highly educated and highly paid individuals who experience considerable job satisfaction, see Cohany (1996, p. 35). This growth in contract work has been discussed by Segal and Sullivan (1997) and Abraham and Taylor (1996). Amongst these predominately white collar workers there has been a considerable decline in job security. As presented in Aaronson and Sullivan (1998), surveys of worker perceptions of job security in the General Social Survey, spanning 1977-1996, carried out by the National Opinion Research Center show that white collar and college educated workers experienced substantial increases in job insecurity in the 1990s. The period also corresponded with a "sea-change" in the norms and expectations of professional careers, caused by the erosion of internal labor markets, see Smith (1997) and D. Gordon (1996).

This down-ward trend in job security is also reported for the same date by Schmidt (1999). She further breaks down the trend by worker category and finds that, during the 90's both white collar and service sector workers experienced more pessimisim about keeping their jobs whereas blue-collar workers became more optimistic. The trend increase in pessimism about job loss over the period was also present in highly educated workers (those with some college and college graduates) but not for those with only high school education. She also shows that, when controlling for occupation, education and age, the fears of job loss increased over the period 1991-96 relative to its level from 1982-90.

*Turnover*. Surprisingly, though there has been a well documented increase in the number of workers that are working under explicitly short-term arrangements, there was initially little evidence of an increase in turnover rates. Diebold, Neumark and Polansky (1997) and Farber (1998) focusing on average job tenure, found these to be relatively constant from the 70s. However, a recent study by Boisjoly, Duncan and Smeeding (1998) using the Panel Study of Income Dynamics (PSID) found that involuntary seperations for men with strong labor market attachment increased from the early 70's to the early 90's. This was also found by Valletta (1998) for involuntary seperations into unemployment, using the CPS over the same period. Using the Displaced Worker Survey, others have found high rates of displacement in the early 90's due to abolition of position or shift and plant closings over the period 1993-95, see Kletzer (1998). More recently, Valletta (1999), using the PSID, has shown a significant decline from 1976-1993 in incentives to maintain existing employment relationships for male workers and skilled females. There is also evidence, presented in Idson and Valletta (1996) that involuntary separations of high tenure workers sometimes reflected employer breach of implicit employment contracts.

### 1.2 Structure of the paper

Section 2 of the paper develops the basic model. This is largely a standard Schumpeterian model of growth except that we allow for incomplete contracting in production. The severity of this contracting problem will be seen to vary with the expected productive lives of firms. We introduce sectoral heterogeneity, so that these lifetimes may vary across industries. Section 3 considers the steady state implications of the model, both with and without contracting incompleteness. We first consider the effect of an exogenous increase in the productivity of research in the benchmark model, treating the contracting environment as fixed. This captures the effect of the IT revolution in opening up new vistas and possibilities. The model is shown to display the usual scale effects common to such R and D based growth models.

The next section then modifies the benchmark model by allowing for contractual incompleteness. Here, human capital sellers and buyers cannot write binding agreements over the particulars of their production arrangement. We allow only self-enforcing contracts, and show that the contracting structure endogenously varies with the change in the economy's human capital endowment. This is the most important analytical section of the paper. Contracting is adversely affected by the increase in arrival rates induced by the increase in R and D and we here demonstrate the conditions necessary for a slowdown to occur. This section also yields an explanation for observed changes in inequality and the distribution of earnings over the same period which we also discuss. Section 4 concludes.

## 2 The Benchmark Model

Our analysis follows closely that of Aghion and Howitt (1992) and Grossman and Helpman's (1991) Schumpeterian model of growth through creative destruction. The numeraire final good $y(t)$ is produced by using intermediate goods, $x_j(t)$, that are distributed uniformly over the unit interval, according to the following Cobb-Douglas technology:

$$\ln y(t) = \int_{j=0}^{1} \ln x_j(t)\, dj$$

These intermediate good industries are further differentiated into $M$ types or sectors, where types are indexed by $m$. These types are differentiated by the step size in the quality ladder, $\gamma_m$. This step size represents the size of an incremental improvement, or innovation in one of the industries in sector $m$.[6] We assume a measure $\frac{1}{M}$ of industries within each sector. Without loss of generality, we order these sectors such that $m < m+1$ implies $\gamma_m < \gamma_{m+1}$. Let a measure $N \geq 1$ denote the amount of human capital in the economy. Each worker can be thought of as possessing one unit of human capital and these workers are endogenously allocated between research and production such that there are $L$ production workers and $R$ research workers; $L + R = N$. Since our interest is in productivity growth, we focus on the allocation of that portion of the economy's labor stock with enough human capital to contribute to growth generating activities (which we term research). We thus ignore other potential inputs, such as unskilled labor, and assume that all the human capital in the model is perfectly substitutable between production and research.[7]

Intermediate industries are operated by monopolists using human capital as the only input to production. At any time, the current monopolist in an industry is the firm which has developed the state of the art production technique, over which it has an infinitely lived patent. Thus, if at time $t$, there have been $n_j(t)$ innovations in industry $j$ the monopolist holding the $n_j(t)\,th$ innovation produces according to the production function $x_j = \gamma_j^{n_j(t)} L_j$, where $L_j$ is the human capital used by the monopolist in industry $j$ for production. Therefore, the monopolist's cost of producing $x_j$ is $\frac{w^j(t)}{\gamma_j^{n_j(t)}} x_j$, where $w^j(t)$ is the wage paid in industry $j$.

[6] We could have modelled all sectors as having the same size of quality step, and only being differentiated by having different innovation probabilities. This would not qualitatively alter our findings.

[7] We thereby abstract from issues of human capital accumulation and ability-biased technological change that may lead to a slowdown through different channels as in Galor and Moav (1999), Galor and Tsiddon (1997), and Helpman and Rangel (1999).

Due to the unit elasticity of demand, implied by the Cobb-Douglas final good production technology, monopolists wish to set the price of intermediate goods as high as possible. Therefore, they limit price at the marginal cost of production using the previous technology. Thus, the unit price of $x_j$ is $\frac{w(t)}{\gamma_j^{n_j(t)-1}}$.[8]

This implies that the firm in industry $j$ earns profit, $\pi^j(t) = [\frac{w(t)}{\gamma_j^{n_j(t)-1}} - \frac{w^j(t)}{\gamma_j^{n_j(t)}}]x_j(t)$. The Cobb-Douglas structure implies that the demand for the good is $x_j(t) = \frac{y(t)}{p_j}$, where $y(t)$ is the total amount of the final good, and since its price is the numeraire, it is also the total expenditure. This implies that $x_j(t) = \frac{\gamma_j^{n_j(t)-1} y(t)}{w(t)}$, and that the amount of human capital demanded in industry $j$ is $L_j = \frac{y(t)}{\gamma_j w(t)}$.

Note that profits are a function of the quality step $\gamma_j$ and the wages $w^j(t)$ paid. In equilibrium, the level of profit and therefore of $\gamma$ will determine how much innovation is undertaken and this will correspondingly determine the wage and effort pairs that are viable.

Individuals consume the final good according to the following identical CES utility function, with discount factor, $\rho$, and are assumed to die with proability $1-\delta$ each period:

$$u(t) = \sum_{\tau=t}^{\infty} \left[ \left( \frac{\delta}{1+\rho} \right)^{\tau - t} c(\tau)^{\sigma} \right]^{\frac{1}{\sigma}}$$

Workers are replaced when they die to maintain a constant population size.

## 2.1 Innovation problem

Let $S_j(t)$ be the total number of researchers in industry $j$ at time $t$ and $\alpha\Phi(S_j(t))$ is the probability of an innovation arriving in industry $j$ in period $t$. $\Phi$ is assumed to be increasing and concave with $\Phi(0) = 0$ and $\Phi(N) < 1$, and $\alpha < 1$ is a technological parameter.[9] We assume that each researcher in industry $j$ has an equal probability of having the first innovation in period $t$, denoted $\alpha\phi(S_j(t)) = \frac{\alpha}{S_j(t)}\Phi(S_j(t))$. The concavity of $\Phi$ is sufficient to render $\phi$ also concave, and it is also the case that $\phi$ is decreasing in $S_j$. That is, the probability of an individual being the first innovator falls with the number of innovators. There is free entry into research activities in all sectors, so that researchers will enter up until expected returns equal opportunity costs. Letting $V^j(t+1)$ be the lifetime expected value of a successful innovation at $t$, researchers will enter up until $\alpha\phi(S_j)V_{t+1}^j = w(t)$. Since the per period profit in period $t$ is denoted $\pi^j(t)$, and

[8]Note that $w(t)$, denotes the unit labour cost were production to be undertaken using the old technology. It will be seen subsequently that this does not vary across industries and that it does not necessarily equal the prevailing wage in industry $j$, $w^j(t)$.

[9]We assume that after one innovation arrives all researchers stop researching until the next period. This is justified where innovators find out about a competitor's success immediately and thus stop researching until the details of the competitor's success become freely available, i.e., until the next period when the competitor sets up in production. At this point, research efforts start afresh. This also simplifies the analysis by avoiding multiple innovations by different firms within a given period.

is stationary in steady state (so, $\pi^j(t+1) = (1+g)\pi^j(t)$ for all t), we can rewrite $V^j(t+1)$ as $V^j(t+1) = \frac{\pi^j_{t+1}}{1-(1-\alpha\Phi(S_j))\frac{(1+g)}{(1+r)}}$ where the stream of profits are discounted by not only the firm's discount factor (the rate of interest), $r$, but also by the expected future innovation rate, $\alpha\Phi(S_j)$,and the growth rate of the economy. As in Aghion and Howitt (1992), this additional discount arises due to the possibility of a future innovator succeeding and usurping the incumbent's leading position.

In steady state, $S_j$ will solve

$$\frac{\alpha\phi(S_j)\pi^j_{t+1}}{1-(1-\alpha\Phi(S_j))\frac{(1+g)}{(1+r)}} = w\,(t)\,. \tag{1}$$

Given the assumptions on $\phi(S_j)$ and $\Phi(S_j)$, higher instantaneous profits imply more innovative effort, $S_j$, is undertaken ceteris parabus.

## 2.2 Stationary Steady State

First, we characterize the stationary steady state equilibrium, while assuming away any contracting problems in production.[10] That is, firms are all able to engage in traditional labor relationships, they can credibly commit to paying workers for labor effort. In reality, the issue is not simply a commitment to pay, but instead all of the elements of deferred compensation that characterize traditional labor relations, i.e., promotion opportunities, increased responsibility and job security. Later, we explicitly examine how the firm's ability to make these commitments may vary with the state of the macroeconomy or its sectoral particulars. Given the similarities between the benchmark model and those of Aghion and Howitt (1992) and Grossman and Helpman (1991), we are deliberately brief in describing the equilibrium conditions here, but they are treated more fully in the next section.

## 2.3 No Contracting Issues

We proceed by conjecturing that, in steady state $y(t) = cw\,(t)$, where $c$ is a constant. This will be verified subsequently. Recall that investment in innovation is given by the following first order conditions:

$$\frac{\alpha\phi(S_j)}{1-(1-\alpha\Phi(S_j))\frac{(1+g)}{(1+r)}}[1-\frac{1}{\gamma_j}]y(t+1) = w\,(t) \qquad \text{for all } j. \tag{2}$$

Substituting in $y(t) = cw\,(t)$ and $y(t+1) = (1+g)y\,(t)$, the allocation of the economy's total human capital endowment, $N$, is given by

$$\frac{\alpha\phi(S_j)}{1-(1-\alpha\Phi(S_j))\frac{(1+g)}{(1+r)}}[1-\frac{1}{\gamma_j}] = \frac{1}{(1+g)c} \tag{3}$$

[10] Although there also exists another equilibrium in which the economy cycles between high and low growth driven by expectations, we focus solely on the stationary steady state.

where

$$N = \int_0^1 [L_i(t) + S_i(t)]di, \quad \text{given } L_i(t) = \frac{y(t)}{\gamma_i w(t)}. \tag{4}$$

Since all sectors are symmetric, output can be expressed as:

$$\ln \; y(t) = \int_0^1 [\ln(\gamma_j^{n_j(t)} \frac{y(t)}{w(t)})]dj$$

Since, in steady state, $y(t) = cw(t)$, then,

$$\ln \; y(t) = \Sigma_{m=1}^{M} \frac{1}{M}[\ln \; \gamma_m^{n_m(t)} + \ln c].$$

So, the growth rate is given by

$$g = \ln \; y(t+1) - \ln \; y(t) = \Sigma_{m=1}^{M} \frac{1}{M}[\ln \; \gamma_m^{n_m(t+1)} - \ln \; \gamma_m^{n_m(t)}]$$

$$= \Sigma_{m=1}^{M} \frac{1}{M} \ln \; [\gamma_m^{n_m(t+1)-n_m(t)}]$$

$$= \Sigma_{m=1}^{M} \frac{1}{M} \ln \; [\gamma_m^{\alpha\Phi(S_m)}]$$

$$g = \frac{\alpha}{M} \Sigma_{m=1}^{M} \Phi(S_m) \ln \; \gamma_m. \tag{5}$$

This expression looks exactly like the Grossman and Helpman (1991) expression for growth. We now verify the steady state conjecture:

Using the production labor market clearing condition (noting that the proportion of the work force in research is constant over time, in steady state),

$$\sum_{m=1}^{M} \frac{1}{M} L_m(t) = \sum_{m=1}^{M} \frac{1}{M} \frac{y(t)}{\gamma_m w(t)}$$

$$= \sum_{m=1}^{M} \frac{1}{M} L_m(t+1) = \sum_{m=1}^{M} \frac{1}{M} \frac{(1+g)y(t)}{\gamma_m w(t+1)}$$

This implies

$$\frac{1+g}{w(t+1)} = \frac{1}{w(t)}.$$

So, the conjecture is verified, $w(t)$ grows at the same rate as $y(t)$. Finally, the rate of change in consumption is related to the growth rate through the consumer's intertemporal optimization problem. Given the CES preferences, this problem is solved as:

$$\frac{c\,(t+1) - c\,(t)}{c\,(t)} = \left(\frac{\delta(1+r)}{1+\rho}\right)^{\frac{1}{1-\sigma}} - 1. \tag{6}$$

The interest rate, $r$, is thus determined by taking $g$ determined from (5) and noting that, in steady state $\frac{c(t+1)-c(t)}{c(t)} = \frac{y(t+1)-y(t)}{y(t)} = g$.

The existence of a steady state almost analogous to the one above has already been well analyzed so that we will not dwell on it further here, see Grossman and Helpman (1991) and Aghion and Howitt (1992).

## 3 The model with incomplete contracts

We now assume that there is moral hazard in production and incomplete contracting. A simple form of incompleteness arises if we assume a worker's output is non-observable to third parties, but known to both worker and firm only after a lag of one period. The non-third party verifiability precludes the use of contracts linking worker payment to output produced. We shall assume that this incompleteness only occurs in intermediate production, not in the research sector where we suppose that research can be undertaken by private individuals who, since working alone, do not face moral hazard.[11] Formally, contracting incompleteness arises due to information limitations as follows.

ASSUMPTION 1:

*Public information*: All workers and firms know the identity of employers and their employees, in all previous periods. The particulars of the worker/firm relationship, in particular whether promised bonuses are paid by the firm, or promised effort is contributed by the worker, are not known publically.

*Worker's private information*: At each period $t$, a worker knows her own wage payments, $w(\tau)$ for all previous periods $\tau < t$, and her own work performance for all periods $\tau < t$. In addition, she knows whether firms in which she was employed in any period $\tau < t$ had delivered any promised deferred payments to her.

*Firm's private information*: At each period $t$, a firm knows the history of wage payments made to all of its past workers by it in all periods $\tau < t$. It also knows the effort contribution of its employees whilst employed with the firm, in all periods upto $t$.

A worker's effort contribution in period $t$ is not observable to the firm in which it is employed until the end of the period. In any case, contracts can only be written on verifiable, and hence public, information. Thus, it is not possible to write a contract which ties a worker's payment to their effort contribution at a particular firm, since, even though this is known to the worker and firm eventually, it cannot be verified by a third party. Malcomson (1999) discusses the advantages of such an approach to analyzing real-world employment relationships, and provides a survey of this literature.

In general, there are two types of implicit contract (termed relational contracts in this environment) that can solve the incomplete contracting problem and yield incentive compatible self enforcing contracts: one allows for the worker to be subject to moral hazard in effort and the

[11]This is for simplicity only, we could have also introduced it in the research sector, the effects would not differ qualitatively from those in this simpler version of the model. However note that in the present version there is no expected surplus in R and D. Of course, the model would have to be altered such that there would exist sufficient surplus to allow agents to get around this contractibility problem.

other allows for the firm to be subject to moral hazard in payment. We shall refer to the first case as the case of "contractors"; and the second case as that of an "internal labor market".

### 3.1 The contractor case

In the case when firms hire contractors, the moral hazard problem resides with the workers. These individuals contract their labor services to the firm on a per period basis. The contractual relationship specifies a payment to the contractor, which is made by the firm at the start of the period; hence before the contractor's effort has been applied to production, and before the firm observes effort. At the end of the period, the firm observes the contractor's effort. If the correct effort was exerted, the implicit contract specifies the contractor will be re-hired in the next period, under the same implicit contract. If not, they will be dismissed.[12] Thus the contractor's reputation, and the potential for future above market clearing returns that it affords, provides incentives to contribute the promised effort.

For it to be incentive compatible for these contractors to supply correct effort, the wage they are paid must be sufficiently greater than their opportunity costs. We denote this incentive compatible contractor's wage by $w^c(t)$ and note that these contractors live another period with probability $\delta$, since they are simply agents in the model. The contractor's incentive compatibility constraint must guarantee that the contractor has a higher discounted utility from not shirking than from shirking in period $t$. In this environment with its perfect capital markets, it is sufficient to consider the present discounted income associated with either choice. As a consequence, a contractor's incentive constraint in period $t$ can be represented by:

$$\Sigma_{\tau=t}^{\infty}\left(\frac{\delta}{1+r}\right)^{\tau-t} w^c(\tau) \geq w^c(t) + \Sigma_{\tau=t}^{\infty}\left(\frac{\delta}{1+r}\right)^{\tau-t} w(\tau). \tag{7}$$

If a contractor produces the correct amount, he continues to receive the payment $w^c(t)$ each period. This is because, even if the current monopolist turns over, his reputation as a reliable contractor in that industry persists, consequently the new incumbent will hire him as well. Hence, we obtain the left hand side of (7). If a contractor shirks, he takes the contract but does not provide the correct effort. The optimal form of shirking here will be to provide no effort for the firm, but instead work elsewhere and obtain the value of labor effort on the market, $w(t)$. In subsequent periods, a shirker will never again be hired as a contractor and must always work at the going wage $w(t)$.[13] This, then, yields the right hand side of (7).

[12] We keep discussion of the strategies which support this implicit contract informal in the text and provide a more formal treatment of the equilibrium strategies in the appendix. We could easily assume that the probability that shirking is detected is less than one; however, this would not qualitatively affect the results. This type of implicit contract corresponds to an efficiency wage as denoted by Shapiro and Stiglitz (1982).

[13] This assumption is for simplicity and arises from the stationarity of the model in steady state. With probabilistic turnover, individuals would transition out of and into employment in steady state, but the qualitative nature of the equilibrium would be unchanged.

Substituting in the steady state conditions, $y(t+1) = (1+g)y(t)$ and $y(t)$ is proportional to $w(t)$, into condition (7), the binding incentive compatible wage is:

$$w^c(t) = \frac{1+r}{\delta(1+g)} w(t).^{14} \tag{8}$$

We leave to the appendix formal statement of the strategies played by workers and firms which support this as an equilibrium outcome.

The wage premium paid to a contract worker is decreasing in the growth rate $g$. This is because, when the economy is growing quickly, people value their future relationships more since they hold in store higher expected value, and therefore a smaller premium is required today to induce effort.[15] In contrast, in a slowdown, the opposite is true. So when growth slows, there is an increase in the disparity between contractor and employee wages, a point to which we return later.

### 3.2 Internal labor markets

Recall that intermediate production occurs in firms owning the state of the art technology in their sectors. Usually, these firms do not have a significant role in this type of growth model, since their profits are distributed to the dispersed shareholders of the economy, and it is assumed they simply hire labor at the going wage, see Grossman and Helpman (1991). Here, however, we identify firms with their incumbency as owners of the state of the art technology. This has already been done implicitly in calculating the discounted value of future firm profits, $V$, which depends on the firm's expected lifetime, $\frac{1}{\alpha\Phi}$.

If firms can credibly commit to paying employees in the future for effort exerted today, there exists another solution to the non-contractibility problem which we term an internal labor market. The implicit contract between worker and firm, in this case, specifies that the worker contributes effort up front in promise of deferred payment. At the end of the period, when the firm can personally verify the worker's contribution, the worker is paid. The worker undertakes to continue with the firm only if the firm met its promised payment. For this solution to work, it is necessary that firms who renege on promised payments are punished in their future dealings in the labor market. Once again, punishments arise as equilibrium responses to deviating behavior, as specified formally in the appendix. Intuitively, punishment here consists of future workers not believing that this firm will meet their promised payments, and hence choosing to reject offers of deferred payment, i.e. not believing in the firm's promised internal rewards. Given those beliefs, and that

[14] Note that, in steady state, the contractor's payment will bind at this incentive compatible wage in industries with worker moral hazard. This is because for higher contractor wages, workers currently working at $w(t)$ can credibly offer their services as a contractor for an amount greater than $w(t)$ but still below the wage of existing contractors, thus upsetting the equilibrium. We return to this in section 3.4.

[15] Note that with CES preferences this is not swamped by the increase in interest rate except the logarithmic, $\sigma = 0$, case.

strategy of workers, the best response for firms who have cheated in the past is to, in fact, cheat any worker who does accept a job, since given their reputation is already destroyed they suffer no additional reputational loss.[16]

This relational contract solves the moral hazard problem in production if firms value their reputations for honest dealing with employees sufficiently. This depends on their discount rate and their length of expected incumbency. Since a firm only lives profitably until the next innovation arrives in its industry, it discounts future profits by the probability of an innovation arriving as well as the discount factor, $r$.

A critical difference between this solution to the moral hazard problem, and the previous contractor solution, is that the firm need only promise to pay workers the going wage, $w(t)$, at the end of the period. There is no need for a wage premium. However, if they cheat and fail to pay workers, they obtain $y(t)$ today without cost in the current period, since the optimal form of cheating will be to renege on all payments. The cost to cheating is that then they can only continue to produce in the future by contracting out production, hence by paying $w^c(t)$, which was determined above. This implies that their incentive compatibility constraint is given by

$$[1-\frac{1}{\gamma_j}]y(t)+\left(\frac{1-\alpha\Phi}{1+r}\right)[1-\frac{1}{\gamma_j}]y(t+1)+\left(\frac{1-\alpha\Phi}{1+r}\right)^2[1-\frac{1}{\gamma_j}]y(t+2)+.....$$

$$\geq y(t)+\left(\frac{1-\alpha\Phi}{1+r}\right)[1-\frac{w^c(t+1)}{\gamma_j w(t+1)}]y(t+1)+\left(\frac{1-\alpha\Phi}{1+r}\right)^2[1-\frac{w^c(t+2)}{\gamma_j w(t+2)}]y(t+2)+.....$$

which can be expressed as:

$$\left(1-\frac{1}{\gamma_j}\right)\sum_{\tau=t}^{\infty}\left(\frac{1-\alpha\Phi}{1+r}\right)^{\tau-t}y(\tau)\geq y(t)+\sum_{\tau=t+1}^{\infty}\left[1-\frac{w^c(\tau)}{\gamma_j w(\tau)}\right]\left(\frac{1-\alpha\Phi}{1+r}\right)^{\tau-t}y(\tau).$$

Using our equilibrium conjectures, and the derived relationship between $w^c(t)$ and $w(t)$ this condition simplifies as follows:

**Lemma 1** *A necessary and sufficient condition for firms' incentive compatibility conditions to hold is that their industry's probability of receiving a successful innovation, $\Phi$, satisfies*

$$\alpha\Phi\leq 1-\delta. \tag{9}$$

We denote

$$\alpha\Phi^*=1-\delta. \tag{10}$$

Any industry with an innovation rate greater than $\alpha\Phi^*$ cannot credibly maintain an internal labor market and must hire contract workers. It is also important to note a high value of $\alpha$, a

[16] Once again, we specify the precise strategies supporting this "hiring" equilibrium in the appendix. See also Bull (1987) for an early version of a firm moral hazard solution to the contracting problem.

high efficiency of research effort, implies that it is harder to hire employees. The intuition for this cut–off is subtle. Firms, if they cheat their workers, must pay future workers their incentive compatible wage from then on. This embeds the worker's incentive constraint within the firm's constraint. Firms and workers trade of the benefit of cheating today against the cost of a loss in the future. They each discount the future using the rate of interest, and the rate of growth. A worker also discounts by the probability of leaving the labour market, $1-\delta$. While a firm discounts by the probability of leaving production, $\alpha\Phi$. The firm's incentive constraint will hold given that the worker constraint holds if and only if the firm values the future at least as much as the worker. So, the constraint will hold if and only if $1-\alpha\Phi \geq \delta$.

### 3.3 Effects of Contracting on Firms

What if the constraint in Lemma 1 fails to be satisfied in some sectors? In particular, suppose that there exists a $\gamma^*$ with implied $\alpha\phi^*$ such that incentive constraints are satisfied for all $\gamma_m \leq \gamma^*$, and therefore, these industries can employ workers at wage $w(t)$. Industries in sectors $\gamma_m > \gamma^*$ however cannot satisfy their incentive constraints, and therefore have to hire in contractors, at a higher wage, to undertake the production labor that is being undertaken by employees in the other sectors. (Recall that absent any contracting difficulties, innovations arrive more rapidly in sectors with higher values of $\gamma$. As a consequence, firms in these sectors will be the ones who find it most difficult to commit to their employees.)

It is clear, from the monopolist's problem, that this change in the wage will alter their labor demanded in production:

$$L_m(t) = \frac{y(t)}{\gamma_m w^m(t)},$$

where $w^m(t)$ is the wage paid in an industry in sector $m$.

Firm profits in industry $j$ are now given by

$$\begin{aligned}\pi_j(t) &= [\frac{w(t)}{\gamma_j^{n_j(t)-1}} - \frac{w^j(t)}{\gamma_j^{n_j(t)}}]\frac{\gamma_j^{n_j(t)-1}y(t)}{w(t)} \qquad (11)\\ &= [1 - \frac{w^j(t)}{\gamma_j w(t)}]y(t)\end{aligned}$$

Note that, in order for production to occur at all, it is necessary that $w^j(t) < \gamma_j w(t)$. If this is not the case, then the cost of labor is too great for any firm to function profitably in this sector.[17] When a technology becomes obsolete, its value to the owner is zero, and since it is public information, it can be used by any individual. It is the free availability of obsolete technologies that forces the new industry leader to limit price at the opportunity cost of human

[17] Note that this condition holds trivially if, in equilibrium, $w^j(t) = w(t)$.

capital producing with the old technology, i.e. $w(t)$. In that case, the maximized value of profit is given by:

$$\pi_j(t) = [1 - \frac{w^c(t)}{\gamma_j w(t)}]y(t) \tag{12}$$

where $w^c(t)$ is given by equation (8). Profits will be positive in all industries provided $\gamma_j$ is sufficiently high. A sufficient condition for this is:

ASSUMPTION 2: $\gamma_1 > \frac{1}{\delta}\left(\frac{1+\rho}{\delta}\right)^{\frac{1}{1-\sigma}}$.

Recall that $\gamma_1$ is the value of $\gamma$ in the lowest sector, so this condition will also hold in all other sectors. Since $g \geq 0$, this ensures (11) is positive, and that production is feasible when hiring contractors.[18]

The innovation problems remain essentially unchanged except that now the expected value of an innovation is a function of the contracting environment. Innovation levels are then implied by the following expressions in all $j$ industries where contractors operate,

$$\frac{\alpha\phi(S_j^c)}{1-(1-\alpha\Phi(S_j^c))\frac{(1+g)}{(1+r)}}[1 - \frac{w(t)}{\gamma_j w^j(t)}]y(t+1) = w(t), \tag{13}$$

where $S_j^c$ denotes the number of researchers in an industry that is constrained to hire contractors. In those industries where producers can credibly hire labor, innovation levels are given by the same relationship as in Section 2.3, that is:

$$\frac{\alpha\phi(S_j)}{1-(1-\alpha\Phi(S_j))\frac{(1+g)}{(1+r)}}[1 - \frac{1}{\gamma_j}]y(t+1) = w(t) \tag{14}$$

Labor market clearing is still given by,

$$\begin{aligned} N &= \int_0^1 [L_j(t) + S_j(t)]dj, \qquad (15) \\ \text{where } S_j(t) &= S_j \text{ for hiring industries} \\ \text{and } S_j(t) &= S_j^c \text{ for contracting industries} \\ \text{and } L_j(t) &= \frac{y(t)}{\gamma_j w(t)}. \qquad (16) \end{aligned}$$

Assuming, for now, that there exists a value of $\gamma$ denoted $\gamma^*$ such that for $\gamma_m > \gamma^*$ production occurs by contracting, and for $\gamma_m \leq \gamma^*$ production occurs by hiring, then the growth rate is calculated as:

$$g(N) = \frac{\alpha}{M}\Sigma_{m=1}^{m^*}\Phi(S_m)\ln\gamma_m + \frac{\alpha}{M}\Sigma_{m=m^*+1}^{M}\Phi(S_m^c)\ln\gamma_m, \tag{17}$$

where, in the above equation, industries are grouped by common values of $\gamma_m$. Finally, the interest rate is determined, as in Section 2.3, from consumer's preferences, equation (6). The formal definition of an equilibrium is given in the following section.

[18] This assumption is made for convenience only. If this were not to hold in some low $\gamma$ sectors, innovation would simply stop in those industries, which, as will be seen subsequently, would further enhance the slowdown.

### 3.4 Equilibria with contracting incompleteness

An equilibrium, or steady state, is a number of research workers, $S_j$, and a corresponding labor allocation to production, $L_j$ for each industry, $j$, such that:
**(I)** the labor market clears (equation (15) holds),
**(II)** in sectors where an internal labor market operates, $S_j$ satisfies equation (14) and condition (9) holds,
**(III)** in sectors where contractors undertake production, $S_j$ satisfies equation (13) and condition (7) holds,
**(IV)** in all sectors, $L_j$ satisfies (16),
**(V)** the equilibrium growth rate is given from (17), and,
**(VI)** as in Section 2.3, $r$ is determined by (6).
In addition to these conditions, firms' and employees' strategies must support honest fulfillment of implicit contracts, that is, the equilibrium strategies support conditions (7) and (9), as further elaborated in the appendix.

There may exist multiple steady states, each with different contracting structures across industries, a point which we discuss further below. However it is possible to exploit the similarity between the model here, and that used in Aghion and Howitt (1992) to show that there exists a unique stationary steady state given a fixed contracting structure:

**Proposition 2** *Holding constant the structure of contracts within each industry, there exists a unique stationary steady state.*

Consider further the possibility for multiple steady states, with differing contracting structures, in this framework. To see this, consider a steady state in which at least one industry hires contractors. For such a steady state to exist implies that (9) holds in that industry, and equilibrium strategies are such that they support firms meeting their obligations for promised deferred payments. Now, consider a slight modification of the steady state in which equilibrium strategies in this one industry support contracting instead of hiring. Since the conditions under which contracting can be supported by equilibrium strategies are always satisfied, from Assumption 2, it will always be possible to find strategies which support (7). Also, since a change in one industry has an arbitrarily small effect on aggregate variables, this alteration of the initial steady state will itself constitute a steady state too. In general, the existence of any steady state where production occurs with hiring, implies the existence of another in which hiring is changed to contracting in some, or all, sectors. It is thus not possible to rule out the simultaneous existence of different steady states with differing contracting structures.

How do we then select between differing contracting structures, and hence differing steady states? The strategy we follow here is to pick that feasible contracting structure with the highest implied growth rate.

ASSUMPTION 3: *When there exist multiple, stable, stationary steady states, the economy is in the one with the highest implied growth rate.*

This is always the steady state with the contracting structure in which the most sectors are able to hire employees rather than contractors, since these are hired at opportunity costs, $w^j(t) = w(t) < w^c(t)$, so that innovation profits are higher from equation (11).

Thus, Assumption 3 ensures that production is undertaken within each sector by hiring employees unless this is not feasible. A sector $k$ then will not be able to hire employees only if, were it to do so (while holding employment relations constant in all other sectors), the implied innovation rate in sector $k$, $\alpha\Phi(S_k)$ given by (14) exceeds $\alpha\Phi^*$ given from condition (10). It is immediate from (14) that this problem is more likely to arise in the high $\gamma$ sectors. Intuitively, the high $\gamma$ sectors attract the most research effort, ceteris pararbus, and thus the highest arrival rate of innovations. Consequently these are the sectors in which firms are least able to credibly commit to long term relationships with their employees. We are now ready to show the existence of a unique steady state maximizing the economy's growth rate.

**Proposition 3** *There exists a unique value of $m$ denoted $m^*$ satisfying equilibrium conditions (I)-(VI) that maximizes the economy's growth rate. In this steady state, all sectors $m \leq m^*$ hire workers and* (9) *holds, all remaining sectors $m > m^*$ hire contractors and* (7) *holds.*

There exist many possible steady states, but, from Proposition 2, a unique one for each contracting structure. Assumption 3 is an equilibrium selection device, which focuses our attention on the contracting structure corresponding to that steady state with the highest growth rate. The proposition demonstrates that such a stationary steady state always exists.

## 3.5 Information Technology

There are many effects that the introduction of computers and the general revolution in information can be thought of as having had on production: it can increase the need for training, lead to a substitution of capital for labor, improve distribution, directly change production efficiency, etc. We wish to abstract from all of these and focus purely upon the increase in the availability of information and the speed of the dissemination of new ideas. In this way, we focus purely on the effect of the information technology revolution of speeding the arrival of new ideas (or equivalently of reducing the cost of research). We will posit that this is a truly general purpose technology that improves the research productivity of all sectors, though qualitatively similar results will obtain if only some sectors are affected, or if sectors are affected to different degrees.

To look at the consequences of such a change, we consider the effect of an increase in the technological parameter, $\alpha$, which captures the effect of research on the probability of an innovation arriving. If the contracting structure within industries remains unchanged, this is exactly analogous to the model in Section 2.3, and the rate of growth, given in (5) will increase with the increase in research effectiveness.

But it is not always possible for the contracting structure to remain unchanged. Starting in a situation in which all sectors have internal labor markets (that is, there is no contract work) the effect of increasing $\alpha$ is to eventually make hiring contractors the only solution:

**Proposition 4** *Starting from a steady state in which all firms use internal labor markets, increasing $\alpha$ implies that the number of sectors in which work is performed by contractors rises (weakly). There exists a level of $\alpha$ above which no sectors can use internal labor markets (that is, all work eventually becomes contract work).*

The contracting structure is not impervious to changes in $\alpha$ because the increase in arrival rates, $\alpha\Phi$, eventually renders firms' expected lifetimes short. If short enough, firms cannot credibly commit to providing deferred benefits to employees. This problem arises earlier for industries with higher $\gamma$, since these are the industries that attract proportionately more research, and hence have higher arrival rates, holding all else equal.

As $\alpha$ increases, and a sector becomes unable to hire workers and must hire contractors, we then look for a steady state in which only that sector has changed its contracting, keeping fixed the contracting structure in other sectors, since equilibrium strategies elsewhere will be unaltered, in accordance with Assumption 3. It is in this case, when a sector is transformed from an employee to a contract worker environment, that growth may slow, as described in the following proposition.

**Proposition 5** *If a small increase in the technology parameter implies that a sector (say $\gamma_{m^*}$) changes from hiring employees to hiring contract workers, then growth falls if $\gamma_{m^*}$ is sufficiently close to $\gamma_M$.*

What is the intuition of this result? When a sector shifts contract structure from an internal labor market to contractors, research labor is taken from that sector and reallocated to other sectors. Some of this labor goes to production and some into research elsewhere. From concavity of industry level research functions, the marginal value of labor in research is strictly lower in the sectors where it is reallocated than where it originated. However, the marginal private value of research does not correspond to its social value, since the productive contribution of innovations varies with the contracting structure. In sectors where labor is performed by contracting (relatively high $\gamma$ sectors) innovators receive proportionately less of the returns to innovation than in sectors featuring within firm employment. This distorts the allocation of labor away from the social optimum, with too little occurring in the sectors with high $\gamma$. It is possible then that the reallocation of labor occurring after the change in one sector's contracting structure raises growth by redirecting resources towards the high $\gamma$ sectors. This effect cannot occur if the distortion is not present, hence the effect of a change in contracting structure is unambiguously bad when all sectors were initially equivalent in contracting, or if the sector changing is close enough in $\gamma$ to the high $\gamma$ sectors. Another implication then, is that as more industries shift towards using contract workers, research is increasingly being transferred into sectors with high values of $\gamma$. As a result, the shifting contract structure becomes more likely to increase growth. Consequently, as more industries transform their employment relationships from internal labor markets to contractors, the slowdown disappears.

However, the main point here is that with a change in contracting structure, a slowdown can occur. The next corollary lists the qualitative nature of any changes that accompany a slowdown in this model.

**Corollary 6** *If an increase in $\alpha$ causes a slowdown, then: (i) the proportion of the labor force under short term employment increases, but (ii) turnover does not necessarily increase, (iii) relative returns of workers in high $\gamma$ sectors rise, (iv) income inequality increases and (v) sectors with the largest declines in productivity growth will be the ones that initially had the highest rates of growth*

There can be no slowdown without a restructuring of labor contracts in some sectors. Without such a change, the arrival of innovations simply increases with a rise in $\alpha$, and growth rises.

A lower growth rate lowers individuals' valuations of the future and they must be compensated more immediately to maintain incentives. Since contractors start at higher wages than employees, further changes in the contracting structure along the slowdown, worsen inequality in the earnings distribution by lowering returns to workers while simultaneously increasing the premium to contractors. Since the increase here would not be attributable to observable worker characteristics (for example, education and training levels), unless earnings equations were estimated with information about contract structure, it would be picked up in the residual of an earnings equation.[19] This corresponds well with the findings of Juhn, Murphy and Pierce (1993) where such earnings equations (which are estimated without information about the form of employment contracts) attributed much of the growth in inequality to unmeasured components.

Furthermore, the increases that occur happen in the high $\gamma$ sectors. That is, these will tend to occur in industries where, for given contracting structure, there are higher growth rates. A positive correlation between industry wages and technological change has been observed in many studies, Hodson and England (1986), Dickens and Katz (1987) and Loh (1992). Though, it should be noted that Bartel and Sicherman (1999), by controlling for individual fixed effects, argue that most of this is due to sorting of high "ability" individuals into sectors with higher rates of technological change, something we cannot address here.

[19] This serves to make this model testably different than Galor and Moav's (1999) model with technological change which is ability biased, where ability is unobservable.

The model's implications for turnover are unclear, and further, the sectoral effects are not robust to different specifications of the effects of IT revolution. According to the model, turnover rates rise when $\alpha$ increases in all sectors that do *not* change their contracting structure, since innovation occurs at a faster rate in those sectors due to their increased research numbers. However turnover will in fact slow in any sector that has undergone a shift toward contract workers. This may seem curious since it is maintained that these sectors can no longer support employee relationships due to an implied innovation rate that is too high. The reason is that with an increase in $\alpha$, a steady state with employees no longer exists since the implied industry level innovation rate, were employee relationships to be maintained, is too high to satisfy firm incentive compatibility, i.e., equation (9) fails. In that case, the only stationary steady state where incentive compatibility conditions hold, is one in which contractors operate.[20]

On the one hand then, turnover falls in the sectors that most recently experienced the change in contracting structure, but on the other, turnover can increase in sectors where contracting has remained unchanged, due to the displacement of research labor from the sectors where contracting changed. Thus the net effect on turnover is ambiguous at the aggregate level. This may provide a possible explanation for why perceptions of greater job insecurity as evidenced by worker surveys, (especially among white collar workers, see Aaronson and Sullivan 1998) have not been reflected in aggregate turnover figures in either the US, (Diebold, Neuman and Polansky 1997), or Canada, (Green and Riddell 1997).

With regards to sectoral level implications, we have assumed that the growth in productivity caused by the IT revolution affects all sectors proportionately. However, if this is not the case the model's predictions about sectoral break-downs of turnover will vary. In particular, sectors which experienced no increase in productivity of research due to IT will experience no change in turnover. Sectors experiencing a greater productivity increase will see a decline in turnover when initially changing from an internal labor market to a contractor's market, but if productivity continues to increase they will experience increasing turnover. Since these predictions depend on identifying the initial effect of IT on each sector, which we do not attempt here, we remain circumspect about the model's implications for turnover.

An implication of the slowdown generated by an increasing $\alpha$ is that it is of finite duration. In this framework, productivity can only fall with $\alpha$ increasing if contracts change. In particular,

[20] This also raises the possibility of a shift from the stationary steady state with hiring, to a steady state which cycles between hiring and contracting as in Aghion and Howitt (1992). We have not formally explored such a possibility but it would conceivably involve multiple periods of low innovation activity within a sector due to low expected profits, in which the low probability of innovation arrival, allowed firms to credibly hire labour with the promise of deferred payments. Then, with an innovation, there would be periods of high research activity and correspondingly high expected profits, in which the high probability of an innovation arriving, would require contracting to solve the moral hazard problem. We have purposefully ruled out analysis of such cycling steady states but this will not affect the slowdown result here. This is because any such steady state will also have lower growth, since, in comparison with the hiring steady states, in a cycling steady state, for some periods at least, innovators hire contractors, and the consequent rise in wages lowers incentives to innovate, and hence growth.

when labor hiring practices in all sectors have changed towards contracts there will no longer be the possibility of a slowdown precipitated by further increases in $\alpha$. Though, for $\alpha$ fixed, productivity growth rates will remain at lower levels. However, the slowdown may end even before this point if the high productivity sectors, that have already experienced their change in contracting, start to absorb more research effort displaced from lower productivity sectors, i.e. if $\gamma_{m^*} << \gamma_M$.

The model also provides one explanation for a puzzling component of the empirical record. Over the period of the slowdown, starting in the early 70s, using almost any measure, research and development has increased. According to the model, although, after an increase in $\alpha$, in any sector that changes contracting structure research intensity will fall, the increase in research productivity will induce more research in other sectors that did not undergo a change in their contracting structure. Here it can easily be the case that this second effect outweighs the first yielding an increase in aggregate research. The intuition for why more research doesn't necessarily lead to more growth is that it is not only the aggregate level of research that matters but also its distribution. The differences in contracting structure and thus of relative returns to research across sectors distorts the allocation of research and reduces its contribution to growth.

In this model, we have assumed that population is fixed. However if instead of increasing the technological parameter we increased the population, we could generate similar results. Fixing the contracting structure, a population increase will increase the amount of research being undertaking and therefore the arrival rates of new innovations through a standard scale effect. This interacts with the contracting structure in approximately the same manner as described above. And so, in this model we can generate a short-term negative relationship between population growth and the growth rate. A series of newer versions of technology based endogenous growth already allow for the possibility of a negative relationship between population growth and productivity growth. However, these models (Young 1998, Howitt 1999, and Segerstrom 1999) do not suggest why the slowdown should have occurred when it did. In contrast, our model even when change is motivated by population growth (not technology) relates the macro changes to observed contemporaneous changes in the labor market and thus links the timing of the slowdown to the period of those changes.

In steady state, all wages grow at the same rate. In this model without capital, any transitions associated with a change in the technology will occur instaneously. However in a more general model if the economy were to experience a slowdown-inducing shock and then to gradually transition to a new steady state with the implied greater wage disparity there would have to be a period of time over which contractor wages would increase at a rate faster than wages of workers in internal labor markets. Although this model cannot capture this dynamics, this may be worth investigating in data series in which workers can be identified by their contractor status, something which we leave to future research.

A final point to note is that a firm's productive life is assumed to end when a new innovation arrives. However, in reality, many firms produce more than one type of good. These firms may still be able to provide a form of commitment to employees by shifting them from newly redundant processes to other productive roles. In fact, within any one firm, there will be employees with differing levels of job security, depending on how wedded their employment is to the technology they are using in production. However, it will still be the case that the firm's commitment to any particular employee will vary with that employee's expected productive life with the firm. A firm's capacity to commit to lengthy employment will not necessarily end with the arrival of faster innovations at the industry level, but should still be negatively affected by them. A similar flavor of effect has been explored by Bertrand (1999). She examines whether employment relationships adjust under increased product market competition and found that increased financial pressure (proxied through increased import competition) transformed the employment relationship from one governed by implicit agreements to one governed by the market. An interpretation she forwards, which is consistent with our hypothesis, is that increased competition weakens the enforceability of wage agreements, so that the spot market governs the relationship.

## 4 Conclusion

Other explanations of the slowdown, such as Helpman and Trajtenberg's (1996) explanation based on the dissemination of General Purpose Technologies, or Lloyd-Ellis's (1999) explanation, arising from a fall in supply of qualified workers and hence a reduction in absorptive capacity, are not mutually exclusive. Certainly such supply side effects would similarly slow down growth in our model. The ultimate importance of contending explanations is an empirical issue, which we make no claim to resolve here. A nice feature of our approach is that it suggests the source of increased earnings dispersion which contemporaneously accompanied the slowdown, will be in the residual of earnings regressions, as has been found in the data. Previous explanations, such as Greenwood and Yorukoglu (1997) and Lloyd-Ellis (1999) need to posit a non-observable skill that the market rewards but observers do not detect, in order to explain this increase in the residual. This may in fact be the source of the increased earnings residual but there is no hope of testing this since the variable is unobservable. Here, in contrast, our analysis predicts the precise nature of the variable which is causing an increase in the residual component. The model predicts that the workers with relatively increased earnings will be the contractors.

The model also reconciles perceptions of increased instability in the worker/firm relationship with the relatively unchanged turnover rates observed in the data.[21] Perceptions of instability arise in these relationships because firms no longer undertake to provide commitments of deferred payments as part of a contract of lifetime employment. This is because firms cannot themselves

[21] For a review of the work on changed perceptions of employment relationships see Sullivan (1999).

credibly commit to needing workers in future, and hence persisting with their employment. We have modeled this as firm turnover, but, more realistically, any changes which induce wholesale alteration of production methods, and restructuring, will be sufficient to weaken a firm's commitment, even if the firm itself persists. However, an induced effect of these labor market changes has been a rise in the costs of obtaining skilled workers, which itself induces a reduction in innovative activity, causing a slowdown. Thus the induced effect, causes a force working in the opposite direction to dampen turnover by increasing production stability. The net outcome on turnover rates is thus unclear, and is consistent with unchanged turnover.

Finally, our focus on the division of rents between firms and workers in the innovation process is reminiscent of recent work by Caballero and Hammour (1997). They similarly couch their analysis in an incomplete contracting environment, where firms and workers bargain ex post over the division of surplus to short run relationship specific rents. They argue that increased appropriability of these rents by labor that was caused by institutional change in some European countries during the lates 1960's and early 1970's, induced a long run substitution towards capital intensive, and labor excluding, technologies that were less subject to such appropriation. Consequently, in those countries, it is argued that labor shares and employment fell. Since their focus was on substitution between factors in the orientation of innovation they treated as exogenous aggregate productivity growth, which is the focus here. Further, the institutional source of the exogenous change used there limits their analysis to selected European countries and could not therefore serve as a basis for the slowdown that occurred in, for example, the US or Japan.

# 5 Appendix A:

### 5.0.1 Strategies supporting the incentive compatible incomplete contracts

**Information sets:**

A strategy maps from each player's information set to the set of actions.

Consistent with assumption 2, at any time $t$, all workers and firms know the past history of all firm/worker employment pairs, referred to as their public history. In particular, it is known whether a worker/firm relationship has terminated, though the reasons for it ending (dismissal or quitting) are not known. A worker's public history at time $t$ is denoted $h^w(t)$, with $h^w(t) = 1$ if the worker has not been involved in a termination for any $\tau \leq t$, and $h^w(t) = 0$, otherwise. Similarly, a firm's public history at time $t$ is denoted $h^f(t)$, with $h^f(t) = 1$ if the firm has not been involved in a termination for any $\tau \leq t$, and $h^f(t) = 0$, otherwise. In addition, both workers and firms have some private information. A worker's knows their own effort contribution upto time $t$. For worker $i$, this is denoted $e_i(t)$, with $e_i(t) = 1$ if the worker has contributed promised effort for all $\tau \leq t$, and $e_i(t) = 0$, otherwise. As well, the worker knows the payment history of any firm with which it has been involved. Thus, for firm $j$ the worker $i$ knows whether

$j$ has paid the promised amounts to $i$ in all previous interactions between $i$ and $j$, denoted $p_i^j(t)$. If the firm has paid all amounts that were promised then $p_i^j(t) = 1$, otherwise, $p_i^j(t) = 0$. In the case of no previous interactions, $p_i^j(t) = 1$. Firms know their own private histories and the histories of the workers in their interactions with them. Thus, firm $j$ knows whether it has paid promised amounts to all its workers, if it has then $p^j(t) = 1$, otherwise $p^j(t) = 0$. If a firm has never before promised payments, then $p^j(t) = 1$. Similarly, if a firm has employed an employee $i$, it knows whether the employee has contributed the promised amounts of effort in its employment at $j$, if it has for all $\tau \leq t$ then $e_i^j(t) = 1$, otherwise $e_i^j(t) = 0$. If they have never before interacted, $e_i^j(t) = 1$.

A worker's information set in period $t$ comprises the public histories of all firms and workers upto and including period $t-1$, $h^w(t-1) \cup h^f(t-1)$ as well as the private information they have from their own employment history, $e_i(t-1)$, and the information they have on the set of firms, denoted $F_i$, for whom they have worked$\left\{p_i^j(t-1)\right\}$ for all $j \in F_i$. A firm's information set comprises the public histories of all firms and workers upto and including period $t-1$, $h^w(t-1) \cup h^f(t-1)$ as well as the private information they have from their own history as an employer. In particular, they know $p^j(t-1)$ and the information they have on the set of workers who have worked for them in the past, denoted $E^j$. Where for all $i \in E^j$ they know $\left\{e_i^j(t-1)\right\}$.

**Strategies**:

Denote a worker's strategy by $\sigma^w(t)$. It has two parts: firstly, it specifies a decision of whether to accept or reject every level of wage offer from every firm, these wage offers can be either up front offers, or offers that a firm promises to pay at the end of the period. Secondly, where up front wage offers have been accepted from a given firm, it specifies a decision of whether to work $(e_i = 1)$ or shirk $(e_i = 0)$ for a given firm.

Denote a firm's strategy by $\sigma^f(t)$. It has two parts: firstly, whether to offer up front payments to workers or to offer payments at the end of the period, and the amounts to offer. Then, for end of period payments offered to a particular worker, it specifies whether to honor those payments, $(p_j = 1)$ or not $(p_j = 0)$.

### 5.0.2 Equilibrium strategies for an efficiency wage 'contractor' outcome:

Denote these strategies by $\widetilde{\sigma}^f(t)$ and $\widetilde{\sigma}^w(t)$ :

$\widetilde{\sigma}_j^f(t)$ for firm $j$ - For any worker $i$ with $h^i(t-1) = 1$ and $p^j(t-1).e_i^h(t-1) = 1$, offer $w^c$ from equation (effwage) upfront, for all other workers make no offer. Do not honor commitments to make deferred payments. Note that there is no turnover in the model, separations are actively created by either a quit or a dismissal.

$\widetilde{\sigma}_i^w(t)$ for individual $i$ - accept any non-negative wage offer made upfront, do not accept offers of deferred wage payments. If $w \geq w^c$ and $h^w(t-1) = 1$ and $p^j(t-1).e_i^h(t-1) = 1$, then set $e_i = 1$, otherwise set $e_i = 0$.

These strategies induce, as an equilibrium wage in that sector, the wage $w^c$ with no workers shirking and all firms rehiring the same employees if and only if they do not shirk. To see this, consider first the incentives of a worker to deviate from $\widetilde{\sigma}_i^w(t)$. If the worker shirks, and works elsewhere for the alternative wage of $w(t)$ she cannot be made better off, since under $\widetilde{\sigma}_j^f(t)$ she will never again be hired in an efficiency wage job so that incentive compatible wages are given by equation $(8)$, which defines $w^c$. Consider a firms incentive to deviate from $\widetilde{\sigma}_j^f(t)$. Suppose the firm decides not to dismiss a worker that shirks, then under $\widetilde{\sigma}_i^w(t)$, the worker will shirk again, so dismissing a shirker is optimal. Suppose that the firm decides to dismiss a worker that has not shirked, this makes the worker strictly worse off, but does not increase the firm's profits, thus retaining a non-shirker is a weak best response.

### 5.0.3 Equilibrium strategies for a 'hiring' outcome:

Denote these strategies by $\widehat{\sigma}^f(t)$ and $\widehat{\sigma}^w(t)$ :

$\widehat{\sigma}_j^f(t)$ for firm $j$ - If $\Phi \leq \Phi^*$ as defined in $(10)$, then, provided $h^j(t-1)=1$, and $h^i(t-1)=1$, and $p^j(t-1).e_i^h(t-1)=1$ offer deferred payment of $w(t)$ and honor the payment if and only if the worker sets $e_i=1$. If $\Phi \leq \Phi^*$ and $h^j(t-1)=0$, $h^i(t-1)=1$ and $p^j(t-1).e_i^h(t-1)=1$, then offer an upfront payment of $w^c$. If $\Phi \leq \Phi^*$ and $h^j(t-1)=1$, and $h^i(t-1)=0$, and $p^j(t-1).e_i^h(t-1)=1$, make no offer. If $\Phi \leq \Phi^*$ and $h^j(t-1)=1$, and $h^i(t-1)=1$, and $p^j(t-1).e_i^h(t-1)=0$, make no offer. If $\Phi > \Phi^*$and $h^j(t-1)=0$, $h^i(t-1)=1$ and $p^j(t-1).e_i^h(t-1)=1$, then offer an upfront payment of $w^c$. If $\Phi > \Phi^*$ and not $[h^j(t-1)=0$, $h^i(t-1)=1$ and $p^j(t-1).e_i^h(t-1)=1]$, then make no offer.

$\widehat{\sigma}_i^w(t)$ for individual $i$ - accept any non-negative wage offer made upfront. If an up frontwage offer is such that $w \geq w^c$ and $h^w(t-1)=1$ and $p^j(t-1).e_i^h(t-1)=1$, then set $e_i=1$, otherwise set $e_i=0$. If $\Phi \leq \Phi^*$ and $h^j(t-1)=1$, and $h^i(t-1)=1$, and $p^j(t-1).e_i^h(t-1)=1$ accept a deferred payment of $w(t)$ and set $e_i=1$.

This induces an equilibrium in which workers accept a work offer with deferred payment of $w(t)$, set $e_i=1$, and firms pay workers only if $e_i=1$. In equilibrium, no workers shirk and all firms honor their payment commitments. To see this, note that equilibrium strategies state that a firm who has reneged on payments (and hence had a separation with an employee) will continue to do so. Given this strategy, a worker's best response is not to trust such deferred payments and to instead work only for payments made up front. Then, however, payments satisfying workers' incentive compatibility conditions, $w^c$, will be required to induce effort.

For completeness, it is also necessary to ensure that firms who have been dishonest, and cannot hire employees, cannot simply sell the technology to another firm who has not been dishonest and therefore values the technology more highly than the initial firm. We rule this out informally by assuming that workers believe that any other firm buying the cheating firm's technology will also cheat their workers. Then the value of the technology to other firms will be equivalent to that of the cheating firm, and firms will not be able to get around their cheating by simply going to the market. Such a restriction on beliefs off the equilibrium path is consistent with the equilibrium.

In general, as long as the firm loses some value in selling the technology after cheating, it is possible to construct an equilibrium in which a firm would have an incentive to honor its wage agreements and therefore workers would believe that the new firm was not a cheater and therefore accept employee positions. In such an equilibrium, workers would believe that the firm values its reputation enough to not be willing to incur the cost associated with cheating even if they could subsequently sell their technology. However, if there were no cost to cheating, either through punishment by workers or through value loss in the firm, no firm would ever be able to hire employees since the firm would immediately cheat them and sell the firm for its entire present discounted value to another firm.

# 6 Appendix B:

### 6.0.4 Proofs

*Proof of Lemma 1:* Given $y(t+1) = (1+g)y(t)$, the incentive compatibility condition simplifies to

$$\frac{w^c(t)}{w(t)}\left(\frac{1-\alpha\Phi}{1+r}\right)(1+g) \geq 1.$$

Given $w^c(t) = \frac{1+r}{\delta(1+g)}w(t)$ this directly simplifies to the expression in the lemma.□

*Proof of Proposition 1:* Holding the contract structure fixed across industries, the model is almost a multiple sector version of Aghion and Howitt (1992), in particular, the sectoral allocation of human capital where hiring occurs is given by (14) which is similar to Aghion and Howitt (1992 eq.3.33 p. 333). There are four differences from their framework: (1) $r$ is determined endogenously, (2) for sectors in which contracting is undertaken, instead of hiring, human capital is allocated according to (13), (3) the term $\phi'$ in their analysis (the marginal product) is replaced by $\alpha\Phi/S$ (the average product) here and (4) contracting in production is incomplete. Consider points (2) and (3) first. In sectors where (13) determines the allocation of human capital, Assumption A is sufficient for production to be viable and the concavity of $\Phi$ implies that the distribution of research activity across sectors is unique. Furthermore, since $\alpha\Phi/S$ satisfies the restrictions of $\phi'$ used in Aghion and Howitt, the proof of uniqueness used there applies directly for exogenous $r$. Endogenizing $r$ does not affect this. To see this, note that, in steady state, $g = \left(\frac{\delta(1+r)}{1+\rho}\right)^{\frac{1}{1-\sigma}} - 1$, and $r$ enters negatively into the denominator of the left hand side (LHS) of equation (13). Consider the equilibrating response in $S_i$ for an increase in $g$, all other changes will not affect $r$ and hence the proof of uniqueness (except for an increase in $\rho$ which is trivial). With an increase in $g$ the right hand side falls. In Aghion-Howitt (ie. ignoring the change in $r$) for equality to be restored,

$S_i$ must rise. Now suppose that $r$ is treated as endogenous, then, for an increase in $g$, $r$ also rises. This lowers the denominator on the LHS and thus increases the LHS necessitating an increase in $S_i$ to equilibrate, which is the same as when $r$ was treated as exogenous. Thus endogenizing $r$ yields no change in the equilibrating response of $S_i$ and no change in the uniqueness of the equilibrium. Finally, the incompleteness in contracting implies that production arrangements must be self-enforcing. They will be so if, in sectors where hiring occurs, beliefs are as described by (i) above, and if, in sectors where contracting occurs, beliefs conform with (ii).□

*Proof of Proposition 2:* Proof is by construction. First suppose that human capital is allocated according to (14) in all sectors, that is, labor is hired, not contractors, and estimate $\Phi$ denoted $\Phi^*(M)$ given by (10), (17), and (16). This yields a vector of $S_m$ values, one for each sector $m$. There are 3 possible cases to consider. Case (1): $\Phi \leq \Phi^*(M)\ \forall\ m$. In that case, set $m^* = M$, and all sectors hire labor under (14). This is feasible since (9) holds, and it clearly satisfies Assumption 3, since $S_k$ solving (14) necessarily exceeds $S_k$ solving (13). Case (2): $\Phi > \Phi^*(M)$ $\forall\ m$, so that (9) fails. In that case, set $m^* = 0$. To see that this satisfies Assumption 3, consider a change in one sector, $k$'s production arrangements so that labor is, instead, hired under contract. This lowers the equilibrium allocation of human capital to $k$ since $S_k$ solving (14) necessarily exceeds $S_k$ solving (13). Consequently, $g$ falls from (17) and so does $r$ from (**??**). This implies a fall in $\Phi^*$, so that $\Phi$ will, once again, exceed $\Phi^*$ in all sectors, implying that (9) fails in all sectors. This will continue to be true, irrespective of the contracting structure in industries, since it is true for the most favorable case of all industries hiring labor. Thus it is not possible for any industry to hire labor, all production is undertaken by contractors under (7) yielding $m^* = 0$. Case (3): $\Phi(S_M) > \Phi^*(M)$ but $\Phi(S_1) \leq \Phi^*(M)$. By the monotonic ordering of sectors, this implies that there exists some sector, denoted $m' \in [2, M]$ such that $\Phi(S_{m'}) > \Phi^*(M)$, but $\Phi(S_{m'-1}) \leq \Phi^*(M)$. By the same reasoning as in case (2), sectors $m'$ to $M$ must be contracting sectors. Thus, calculate a revised value for $\Phi^*$ by supposing that (13) holds for all sectors $m'$ and above, while, (14) holds for all sectors $m'-1$ and below. Denote this value $\Phi^*(m')$. If $\Phi(S_{m'-1}) \leq \Phi^*(m')$ then set $m^* = m'-1$. This satisfies Assumption 3, since (9) will hold for all firms equal to and below $m'-1$, and it can never hold for the others. If $\Phi(S_{m'-1}) > \Phi^*(m')$, then calculate a new value of $\Phi^*$ by imposing that all sectors from $m'-1$ and above are contract sectors and thus solve (13). Denote this value $\Phi^*(m'-1)$. If $\Phi(S_{m'-2}) \leq \Phi^*(m'-1)$ then set $m^* = m'-2$. Where, by the same reasoning as above, this value of $m$ is the steady state maximizing the economy's growth rate. If $\Phi(S_{m'-2}) > \Phi^*(m'-1)$ then repeat the same process in the previous step for sector $m'-3$ and so on. Stop when either $\Phi(S_{m'-1-i}) \leq \Phi^*(m'-i)$ and then set $m^* = m'-1-i$, or $i = m'$, in which case $m^* = 0$.□

*Proof of Proposition 3:* This follows immediately from the steady state equations. As $\alpha$ increases, the wage rate falls and the number of researchers in each sector increases, as dictated by the first order condition (14). This increases the innovation rate in every sector that hires employees. Eventually, increasing $\alpha$ will yield an innovation rate that violates each firm's incentive compatibility condition, condition (9). In other words, eventually $\Phi(S_m) > \Phi^*$ calculated from (10) for all sectors $m$.□

*Proof of Proposition 4:* Suppose that sector $\gamma_{m^*}$ goes from being a sector which can credibly hire employees to one that must hire contract workers as a result of the increase in $\alpha$ to $\alpha' > \alpha$. The implied change in the growth rate can be represented as follows

$$\begin{aligned} g(\alpha') - g(\alpha) &= \frac{1}{M}\sum_{k=1}^{m^*-1} log(\gamma_k)[\alpha'\Phi(S_k(\alpha')) - \alpha\Phi(S_k(\alpha))] \\ &+\frac{1}{M} log(\gamma_{m^*})[\alpha'\Phi(S^c_{m^*}(\alpha')) - \alpha\Phi(S_{m^*}(\alpha))] \\ &+\frac{1}{M}\sum_{k=m^*+1}^{M} log(\gamma_k)[\alpha'\Phi(S^c_k(\alpha')) - \alpha\Phi(S^c_k(\alpha))] \end{aligned}$$

where the superscript $c$ denotes that these innovation levels are for a sector that must use contract workers. Given the concavity of $\Phi$ this expression is

$$\begin{aligned} &\leq \frac{1}{M}\sum_{k=1}^{m^*-1} log(\gamma_k)\frac{\alpha\Phi(S_k(\alpha))}{S_k(\alpha)}[S_k(\alpha') - S_k(\alpha)] \\ &+\frac{1}{M} log(\gamma_{m^*})\frac{\alpha\Phi(S_{m^*}(\alpha))}{S_{m^*}(\alpha)}[S^c_{m^*}(\alpha') - S_{m^*}(\alpha)] \\ &+\frac{1}{M}\sum_{k=m^*+1}^{M} log(\gamma_k)\frac{\alpha\Phi(S^c_k(\alpha))}{S^c_k(\alpha)}[S^c_k(\alpha') - S^c_k(\alpha)] \end{aligned}$$

Labor market clearing implies

$$\begin{aligned} 0 &= \frac{1}{M}\sum_{k=1}^{m^*-1}[S_k(\alpha') - S_k(\alpha)] + \frac{1}{M}\sum_{k=m^*+1}^{M}[S^c_k(\alpha') - S^c_k(\alpha)] \\ &+\frac{1}{M}[S^c_{m^*}(\alpha') - S_{m^*}(\alpha)] + L' - L \end{aligned}$$

Substitution for $[S^c_{m^*}(\alpha') - S_{m^*}(\alpha)]$ yields

$$\begin{aligned} g(\alpha') - g(\alpha) &\leq \frac{1}{M} log(\gamma_{m^*})\frac{\alpha\Phi(S_{m^*}(\alpha))}{S_{m^*}(\alpha)}[-(L' - L)] \\ &+\frac{1}{M}\sum_{k=1}^{m^*-1}[S_k(\alpha') - S_k(\alpha)][log(\gamma_k)\frac{\alpha\Phi(S_k(\alpha))}{S_k(\alpha)} - log(\gamma_{m^*})\frac{\alpha\Phi(S_{m^*}(\alpha))}{S_{m^*}(\alpha)}] \\ &+\frac{1}{M}\sum_{k=m^*+1}^{M}[S^c_k(\alpha') - S^c_k(\alpha)][log(\gamma_k)\frac{\alpha\Phi(S^c_k(\alpha))}{S^c_k(\alpha)} - log(\gamma_{m^*})\frac{\alpha\Phi(S_{m^*}(\alpha))}{S_{m^*}(\alpha)}] \qquad (18) \end{aligned}$$

It is sufficient to show that the RHS of (18) is negative as $\alpha' \to \alpha$. First, we will assume that the amount of labour in production is unaltered. So, $L' - L = 0$. For an arbitrarily small change in $\alpha$, the amount of labour allocated to production will not fall. However, it may rise since the sector that switches its contracting structure will release some research workers. However, if the result obtains given this assumption (that $L' = L$) then it will obtain if more labour is admitted to production since this additional removal of some workers from research can only reduce the rate of growth.

It remains to show that

$$\frac{log(\gamma_k)}{log(\gamma_{m^*})} \leq \frac{\frac{\Phi(S_{m^*}(\alpha))}{S_{m^*}(\alpha)}}{\frac{\Phi(S_k(\alpha))}{S_k(\alpha)}} \qquad \text{for } k < m^* \tag{19}$$

and

$$\frac{log(\gamma_k)}{log(\gamma_{m^*})} \leq \frac{\frac{\Phi(S_{m^*}(\alpha))}{S_{m^*}(\alpha)}}{\frac{\Phi(S_k^c(\alpha))}{S_k^c(\alpha)}} \qquad \text{for } k > m^* \tag{20}$$

are negative. To show (19): Substituting from the innovation problem implies that (19) becomes

$$\frac{log(\gamma_k)}{log(\gamma_{m^*})} \leq \frac{1-\frac{(1+g)}{(1+r)}(1-\alpha\Phi(S_{m^*}(\alpha)))}{1-\frac{(1+g)}{(1+r)}(1-\alpha\Phi(S_k(\alpha)))}\frac{\gamma_{m^*}(\gamma_k-1)}{\gamma_k(\gamma_{m^*}-1)}.$$

>From the innovation problem, it follows that $S_{m^*}(\alpha) > S_k(\alpha)$, implying that the first fraction on the right hand side of the above expression is always greater than 1. It is therefore sufficient to show that $\frac{log(\gamma_k)}{log(\gamma_{m^*})} \leq \frac{\gamma_{m^*}(\gamma_k-1)}{\gamma_k(\gamma_{m^*}-1)}$ which follows immediately given $1 < \gamma_k < \gamma_{m^*}$.

To show (20): First note that if $m^* = M$, there is no condition (20) and the proof is concluded. However if $m^* < M$ then a similar substitution to (19) above yields

$$\frac{log(\gamma_k)}{log(\gamma_{m^*})} \leq \frac{1-\frac{(1+g)}{(1+r)}(1-\alpha\Phi(S_{m^*}(\alpha)))}{1-\frac{(1+g)}{(1+r)}(1-\alpha\Phi(S_k^c(\alpha)))}\frac{\gamma_{m^*}(\gamma_k-1)}{\gamma_k(\gamma_{m^*}-1)}.$$

Note that $\frac{log(\gamma_k)}{log(\gamma_{m^*})} \geq \frac{\gamma_{m^*}(\gamma_k-1)}{\gamma_k(\gamma_{m^*}-1)}$ since $\gamma_k > \gamma_{m^*}$. So the result will require that $1-\frac{(1+g)}{(1+r)}(1-\alpha\Phi(S_{m^*}(N)))$ be sufficiently larger than $1-\frac{(1+g)}{(1+r)}(1-\alpha\Phi(S_k(N)))$. It will be larger if $\gamma_{m^*} > \rho(1+g)\gamma_k$. So as $\gamma_{m^*} \to \gamma_k$, (20) will hold for $k > m^*$. And in particular, when $\gamma_{m^*} \to \gamma_M$, this condition holds.□

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