Organizational Depressions*

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Abstract

I develop a general equilibrium model in which organizational capital (OC) plays a central role. I calibrate it and compare its transitional dynamics when the adoption of new methods involves the implicit obsolescence of OC, against data from the productivity slowdown. The model accounts for the puzzling 25-year slump in detremded TFP and output, the depth of the 40% stockmarket slump, and observed cohort effects across establishments. Unlike related accounts, it also generates a prolonged ageing of capital, although the effect is not as large as that displayed in the data.

JEL Codes: D23, E32, N10, O40.

1 Introduction

The magnitude and persistence of the productivity slowdown and the attendant stockmarket dynamics remain a puzzle. Several accounts hinge on the arrival of a new more productive kind of capital, often identified with information technologies (IT) – see for example Hornstein and Krusell (1996) and Greenwood and Yorukoglu (1997). These models, however, cannot necessarily match the persistence of the slowdown, and hinge on an acceleration of equipment obsolescence and replacement. This implies a decreasing average age of capital – a prediction which, however, is starkly at odds with the data.

An aspect of the drastic technical change that the above authors consider is the possible learning costs associated with new technologies. While remaining agnostic as to the identity

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of the underlying shock, I focus on the dynamics of this learning process, and on how certain aspects of it may work as a *propagation mechanism* for that shock.

Brynjolfsson et al (2000) and (2002), among others, study the link between IT investment and plant-level productivity. They find that returns to IT are large, but contingent on the adoption of complementary changes to business organization. I interpret this finding as follows. Aside from whether or not IT is intrinsically more productive than other forms of capital, its *manner of use is different* – sufficiently so that its proper implementation requires a reorganization of the productive process. If establishments develop expertise in the use of a particular process over time, adopting a radically *different* process may entail a substantial loss of process-contingent knowledge. I identify this process-contingent knowledge as *organizational capital* (OC). The *option value* of previously-accumulated OC will thus be a crucial determinant of the decision to adopt a radically new process.

The paper develops a general equilibrium economy in which process-specific learning can play a central role in productivity dynamics. In the model, establishments accumulate OC and at any date may choose to reorganize and adopt a new productive process – the frontier of which expands exogenously over time. Under normal circumstances, although the decision to reorganize and update the productivity process entails certain costs, accumulated learning still applies to new processes – equivalently, there exists a market for information on, or for assistance in, achieving this compatibility.

To this environment, I apply a "disruptive shock" – an *in*compatibility between organizational capital and new processes after a certain date – and compare the model dynamics with those of the productivity slowdown. Remarkably, the decrease in stockmarket capitalization is well above that generated by the other models – especially the 2%-10% drop attributed by Wei (2003) to the direct effect of the oil price shock – matching the observed 40% drop under plausible assumptions on listing delays. Output remains below trend for over 25 years, and output *growth* for 10 years.

Changes to staggered adoption patterns drive the slump in all models with a technological approach to the slowdown. However, the margin of adoption that they focus on – mostly equipment replacement – *accelerates* after the shock. I argue that *delays* are more likely a critical component of the observed dynamics. Some aspects of the model are similar in spirit to Hobijn and Jovanovic (2001); however, they do not present a quantitative exercise, nor do they derive the macroeconomic implications of their model.

Model structure appeals exclusively to concepts that are empirically important for micro-dynamics: plant-specific learning, and lumpy investment patterns. I identify a change in the production process using the magnitude and concentration of large size adjustments. The previous literature has attributed lumpiness to direct factor adjustment costs – e.g. Thomas (2002). However, Prescott and Visschler (1980) show that organizational capital *itself* may endogenously lead to adjustment costs, depending on the object of the knowledge that is being accumulated. While the present notion of OC is not the same as theirs, it embodies their notion that the root of adjustment costs is *informational* rather than direct.

Section 2 reviews the literature on the technological approach to the slowdown in a little more detail. Sections 3 and 4 describe the model and calibrate it to US data. Section 5 then studiesthe transition dynamics resulting from a disruptive shock. Section 6 wraps up.

2 The Slowdown

The productivity slowdown is identified with trends that began in the mid 1970s and lasted well into the 1990s. Changes in investment and adoption patterns have been identified as an important component of the slowdown and the subsequent recovery – see Gordon (1999). Consequently, I restrict myself here to accounts that hinge on such changes.

Greenwood and Yorukoglu (1997) are representative of the "embodied GPT" (General Purpose Technology) approach. Inspired by an increase in the measured rate of equipment-embodied technical change, this account hinges on the arrival of a new technology which is adopted widely. Associated with this technology is an increase in capital-embodied productivity growth. Hypothetically, it is then the widespread espousal of IT itself that leads to a loss in productivity, as the costs of adoption are defrayed. The economy then converges to a new stationary state in which growth is higher and capital is replaced more frequently, depreciating faster relative to the advancing productivity frontier.

Comin (2001) argues against this interpretation. First, since adoptees would be those who suffer an initial productivity loss, the measured rate of embodied technical change should *decrease*. Second, the GPT view implies that industries with widespread IT adoption should have experienced the sharpest slowdowns during the 1970s and 1980s. He finds that in fact the *opposite* was the case, so that the slowdown is better accounted for by a lack of productive advancements among those that *did not* adopt IT equipment. He argues instead that uncertainty increases the rate at which capital becomes obsolete, and that an increase in uncertainty in the 70s led to a demand for newer, more flexible capital – in the form of IT – with *delays in adoption* being responsible for the slowdown. Once these delays have passed, capital replacement accelerates as equipment becomes obsolete faster.

Both the GPT approach and Comin's (2001) alternative share the prediction that the diffusion of new capital-embodied technologies should accelerate. Economic obsolescence is faster, and the replacement of capital is more frequent. This requires a rapid *decrease in the average age of capital.*

The data belie this prediction, however. Figure (1) indicates quite clearly that the tendency has been for average equipment age to *increase*, not just during the 1970s but through into mid-1990s.[1] Wolff (1996) finds that this trend is robust to the inclusion of

[1] Equipment is the relevant class of capital as it is the focus of the above accounts. Also, embodiment

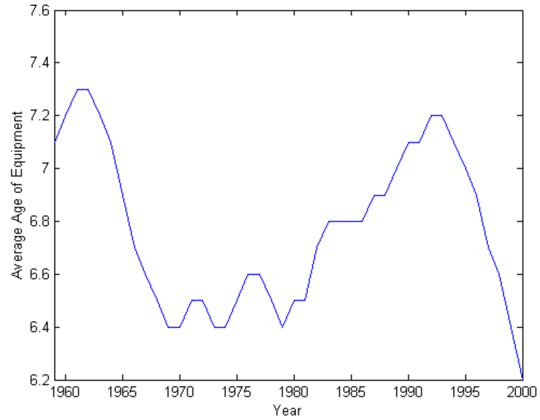

Figure 1: Average age of equipment, US (Source, US Bureau of Economic Analysis)

structures and extends to several industrialized countries that experienced the slowdown.

Perpetual inventory methods imply that an increasing average age of capital must be due either to a sharp decrease in investment – which we do indeed observe in Figure (2) – or to a large change in capital stock composition. A naive computation from aggregate capital could display an upward bias, however, since there has been a shift towards asset classes with shorter service lives (including IT) and possibly a shortening of service lives *within* asset classes. The BEA accounts for the former by taking the asset mix into consideration, and for the latter by imputing economic depreciation rates each period from the second-hand prices of extant vintages – see Hulten and Wykoff (1981).[2] This suggests that the measurement is robust – hence, economic dynamics during the period in question must have been driven by unidentified factors.

This criticism applies to the GPT approach during the entire transition, and to Comin (2001) at the time at which his model implies accelerated adoption. His model attributes the slowdown to an initial *deceleration* in adoption, however, followed by an acceleration. In his model, the slowdown should be reversed after one period of adoption, that is more abbreviated than usual. Doms and Dunne (1998) find that, over the 16 year period of their study, 50% of the investment at the average firm was accounted for by 3 years. This suggests that updating lags last approximately 6 years on average. This is an upper bound on the length of the slowdown that the model yields, so that the slowdown should have been *reversed* within this time frame. Figure (1) suggests that this is a significant underestimate.

is much lower in structures – see Gort et al (1999).

[2]As to whether there is mismeasurement in the capital stock and hence the average of capital due to embodiment, Greenwood et al (1996) shows that aggregate capital is the same regardless of whether or not investment is measured in "efficiency units".

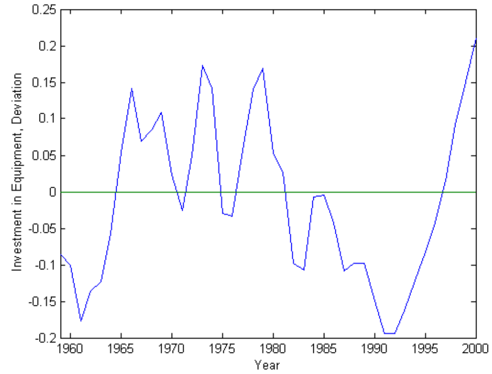

Figure 2: Exponentially Detrended Investment (Source: US Bureau of Economic Analysis)

2.1 Asset Markets

Aside from the real sector, the US ratio of the value of the stockmarket to GDP dropped by 40% in 1974, not attaining its previous level until around 1995, and a related strand of literature has attempted to account for this slump. These works also contend that the source of the slowdown was the advent of IT, which presented new productive opportunities that favored young over old establishments starting sometime in the early 1970s. Hobijn and Jovanovic (2001) argue that this hypothesis is consistent with asset price and cross-industry data over the period. In their models, once it is known that a new technological paradigm based on a new, more productive intermediate good which is not perfectly substitutable with old ones is nigh, incumbents will *not* adopt new technologies and the stockmarket will fall even though there are new productive entrants. This is because it takes several years for firms to reach the IPO stage, so their equity value is initially unmeasured. Capitalization rises again after their IPOs. Thus it is not that establishments are *unprofitable* as such, but rather that the most profitable establishments are unmeasured, while incumbents are disfavored due to an unpromising future. This shares Comin's (2001) prediction that it should be adoptees – and, in particular, new entrants – who buck the downward productivity trend. A disadvantage of this account is that it does not attempt to provide a joint account for both macroeconomic and asset price dynamics.

To summarize, the following stylized facts characterize the period in question:

1. a decrease in detrended productivity that lasts about 20 years
2. a decrease in output growth that lasts about 10 years
3. an increase in the average age of capital of about 8 months between 1973 and 1989, associated with a decrease in detrended investment of about 20% until 1992.

4. a 40% drop in stock market capitalization, lasting about 20 years
5. a boon for young establishments, *vis-a-vis* old ones
6. a boon for adopters of new technologies, *vis-a-vis* non-adopters

None of the above accounts is capable of matching all these facts, particularly the persistence of the slowdown and the increase in the average age of capital.

3 Model Economy

3.1 Productivity

There is a continuum of establishments that exist in discrete time. At any given date t, each establishment is characterized by the age of its productive process τ and its age, or experience using that process, a. The production function is

$$\begin{aligned} & A(\tau, a, t) k_t^{\alpha} n_t^{\beta} \\ A(\tau, a, t) &= \gamma_N^t \gamma_S^{t-\tau} \Omega(a) \end{aligned}$$

where k_t is the amount of capital it uses, n_t is labor.

There are three components to productivity. First, γ_N captures exogenous productivity growth that does not require any sort of adjustment and benefits all. Second, γ_S captures the rate of productivity change that is embodied in organizations. The exponent $t - \tau$ on this factor indicates the point in time at which the establishment adopted its current productive process, either through birth or through updating. Third, $\Omega(a)$ is expertise that an establishment has accumulated regarding the implementation of the process in use. Both τ and a will be elements of OC, in that they determine the extent to which productivity is idiosyncratic. Ω is increasing, concave, and tends to an upper bound $\overline{\Omega}$. Consequently, the adoption of new processes is essential for indefinite productivity growth at the establishment level net of γ_N.

An establishment's productive process embodies the frontier at the time of its birth, and it must make an explicit decision to improve productivity along this dimension, from, say, τ to $v < \tau$. If it chooses to do so, it incurs a cost κ in units of a *managerial input* that is treated in more detail below. κ can be interpreted as a consulting cost that must be paid in order to learn about or implement a new process. Thus, τ identifies the portion of OC for which there is a market, whereas Ω is expertise that must be earned over time. An alternative interpretation is that κ is the cost of making previous knowledge Ω compatible with the new process v.

Updating will be a decision of the (S, s) form.[3] Hence, plant employment and investment patterns will often display by large jumps. Lumpy adjustment is a well known feature of plant dynamics, and has been attibuted to the presence of factor adjustment costs. The model asserts that, rather than being *direct*, it is *informational* costs – in the form of adjustment costs to OC – that drive these patterns.

Plants are born using the frontier process $\tau = 0$, with a level of learning $\Omega(0)$. Each period, establishments die with probability $\lambda(a)$, where function λ is decreasing and convex to capture parametrically the fact that young establishments suffer from higher hazard rates. They discount the future at rate $\frac{1}{1+i}$.

An element that is missing from the model is the possibility of *takeovers*: firms may not appropriate either the OC or the productive process of others simply via direct purchase. Following Hobijn and Jovanovic (2001), I assume that takeovers are an imperfect device to effect this transfer. Faria (2002) develops a related model of OC and mergers on the basis of Ω, finding that although there exist potential gains from such transfers after technological innovations, mergers will wait until the technologies are "mature". Hence, merger activity is unlikely to affect macroeconomic dynamics for most of the period in question.

3.2 Households

A unit continuum of infinitely lived households has standard preferences

$$\sum_{t=0}^{\infty} \beta^t \left\{ \ln c_t + \xi(\Xi - n_t) \right\}$$

where $c_t \geq 0$ is consumption and $n_t \in [0, \Xi]$ is labor. $\Xi > 1$ is their per-period time endowment. There is an institutionally determined work week of length 1, so that all agents are either working time 1 or not working at all. Perfect unemployment insurance is assumed to be available, enabling a recursive representation the household preferences as $\sum_{t=0}^{\infty} \beta^t \{\ln c_t - \zeta n_t\}$ for a constant ζ. Total employment may then be identified with n_t.

Households may allocate their time to either of two activities. First, they supply it to a competitive labor market. Second, they use it to produce the managerial input – that agents must be indifferent between labor and entrepreneurialism in equilibrium will play the role of a free-entry condition. If a household invests e units of labor in this activity, it generates $\phi(e)$ managerial units in return[4]. $\phi' > 0, \phi'' < 0$. The managerial input has two uses: entepreneurship and consulting. The establishment of a new plant requires one unit of the intermediate, whereas updating requires κ units.

[3] For simplicity I have made κ independent of v. Even relaxing this assumption, all updating will be to the frontier. See Samaniego (2002).

[4] Veracierto (1999) endows ϕ with a decision-theoretic foundation in which agents differ in entrepreneurial ability. Lazear (2002) provides empirical evidence that this is the case.

Households own all capital and establishments, earning income from all of these sources. Finally, they spend time producing new establishments and purchasing others for their portfolios. All markets are competitive. Let μ_t be the measure over plant types, K_t be aggregate capital and $X_t = (\mu_t, K_t)$. Their budget constraint becomes

$$\begin{aligned} c_t + k_{t+1} + p_e(X_t)\, q_t &\leq \Pi(X_t) + (1-\delta)\, k_t + r(X_t)\, k_t + w(X_t)\, n_t + p(X_t)\, \phi(e_t) \quad (1) \\ k_t &= \text{household capital asset holdings} \\ q_t &= \text{purchases of new establishments} \\ p(X_t) &= \text{price of the intermediate good} \\ p_e(X_t) &= \text{price of a new establishment}^5 \\ r(X_t), w(X_t) &= \text{rental rate of capital, real wage} \\ \Pi(X_t) &= \text{equity income from establishment holdings} \end{aligned}$$

4 Accommodative Equilibrium

First, consider an environment in which there is no intrinsic incompatibility between productive processes and past learning. I refer to this as the "accommodative" environment, and concentrate on the balanced growth path. A balanced growth path implies a stationary measure over τ and a: in other words, if Γ describes the law of motion for X_t it must be that $\Gamma(X_t) = (X_t)$.

Let $W(\tau, a, \mu_t)$ denote the plant value function. Per-period profits are

$$P(\tau, a, X_t) = \max_{k_t, n_t} \left\{ \gamma_S^{-\tau} \Omega(a) k_t^{\alpha} n_t^{\beta} - k_t r(X_t) - n_t w(X_t) \right\}$$

The continuation value C, the value of updating U and the optimal updating rule Υ are given by

$$\begin{aligned} C(\tau, a, X_t) &= \max\left\{ W(\tau+1, a+1, \Gamma(X_t)), U(a, X_t) \right\} && (2) \\ U(a, X_t) &= W(0, a+1, \Gamma(X_t)) - \kappa p(X_t) && (3) \\ \Upsilon(\tau, a, X_t) &= \begin{cases} 1 & \text{if } U(a, X_t) \geq W(\tau+1, a+1, \Gamma(X_t)) \\ 0 & \text{otherwise} \end{cases} && (4) \end{aligned}$$

Finally, that the value function may be formulated recursively as

$$W(\tau, a, X_t) = P(\tau, a, X_t) + \frac{1}{1+i_t} C(\tau, a, X_t) \tag{5}$$

Proposition 1 *Given Γ, W exists, is decreasing and convex in τ and increasing and concave in a. Updating policies are of the (S, s) form. Updating lags are smaller for older establishments.*

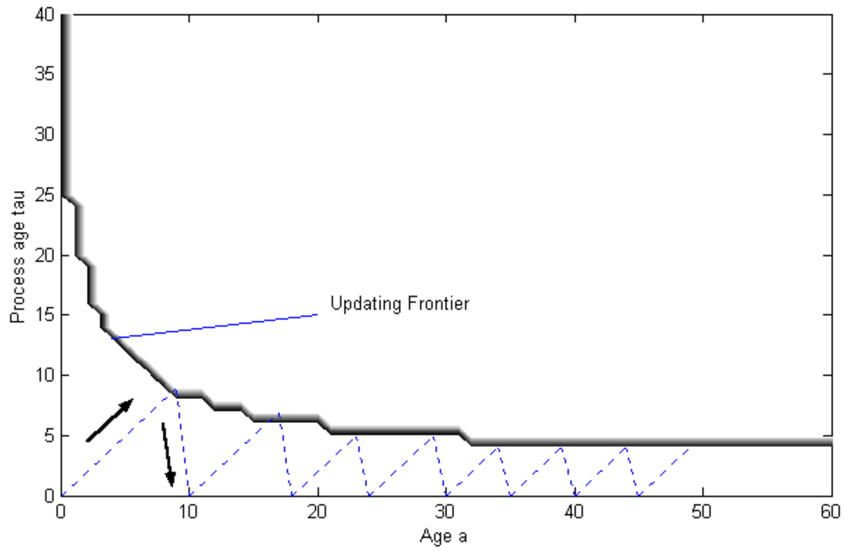

Figure 3: Optimal Updating and Plant Dynamics

Figure (3) illustrates the relationship between the plant lifecycle and updating of the productive process. Establishments begin at point $(0,0)$, with a frontier process but no experience. As they age, they proceed North East until they either die or reach a point on the updating frontier at age a. The following period their process age τ reverts to zero, and they return to the horizontal axis at $a+1$. The shape of the updating frontier reflects the results of Proposition **??**.

4.1 Equilibrium

A recursive competitive equilibrium (RCE) in this context will be the value functions, a law of motion for the aggregate state and price functions of the aggregate state such that

1. All agents are acting optimally given price functions
2. Markets clear at all points in time
3. Price realizations are consistent with the price functions
4. The aggregate state evolution is consistent with agents' decisions.

Market clearing conditions are standard. Let $\Upsilon(\tau, a, X_t)$ be the optimal updating rule for establishments of type (τ, a). The managerial market clearing condition when households behave symmetrically will be

$$\phi(e_t) \geq \kappa \int_{\not{N}^2} \Upsilon(\tau, a, X_t)\, d\mu_t + q_t$$

A stationary equilibrium will be an RCE and a measure over agent types that is replicated every period. This notion is approximate in that the state space is not convex but is rather $\not{N}^2$. The model can be interpreted as an approximation to one in which there is another convex dimension of heterogeneity, which would be burdensome to simulate. Even in transition, however, differences between supply and demand in any of the markets in question were on the order of 0.01% or less. The main effect of the non-convexity of states and decisions is that some aggregates do not always grow smoothly in transition.

4.2 Calibration

I now calibrate the balanced growth path. Period length is set to one year. Parameters were chosen for the stationary equilibrium to match statistics from US data as outlined below. In principle, there is a positive mass of establishments of age a for any $0 < a < \infty$. I choose an upper bound A on age, and assume that all establishments necessarily die when they reach it. Although the (S, s) nature of updating means that there should be some process age beyond which establishments do not proceed, it is nonetheless necessary to pick an upper bound T on τ also. I use $A = T = 100$, which are high enough for there to be a negligible effect on dynamics of changing these values.

4.2.1 Functional forms

In the management literature it is common to assume certain functional forms for learning curves on the basis of ad-hoc criteria. Jovanovic and Nyarko (1996), however, develop a model of Bayesian learning that imbues the learning curve with an information-theoretic foundation. The resulting functional form is sparse, depending only on two parameters, and may be described by the following difference equation:

$$\begin{aligned} \sigma_0^2 &= \sigma^2,\ \sigma_{a+1}^2 = \frac{\sigma_u^2 \sigma_{ja}^2}{(\sigma_u^2 + \sigma_{ja}^2)} \\ \Omega(a) &= 1 - (\sigma_a^2 + \sigma_u^2) \end{aligned}$$

The appendix describes an interpretation of this functional form in terms of a signal extraction problem, based on a simple extension of their model. Note that Ω satisfies the assumed properties: it is monotonic, concave and $\overline{\Omega} \equiv \lim_{a\to\infty} \Omega(a) = (1 - \sigma_u^2)$.

I follow Veracierto (1999) and Samaniego (2002) in setting $\phi(e) = e^{\phi}$.As for λ, Dunne et al (1989) find that hazard rates are decreasing in establishment age. I apply the following

α	β	δ	η	ζ	ϕ
25%	63%	9.19%	0.977	1.0677	0.3

Table 1: Parameter Values 1

form that is decreasing, convex, and bounded below:

$$\lambda(a) = \lambda_1 + \lambda_2 \log[(1/a) - \log(1/A)]$$

4.2.2 Parameter Values

Factor shares can be derived from National Income and Product accounts. I set $\beta = 63\%$, which is in the middle of the range of estimates. As for α, the US Bureau of Economic Analysis reports that income from equity and from proprietorships has averaged 12% of GDP since 1959. Identifying this with the share of income from profits yields $\alpha = 25\%$.

Let γ_Y be the growth factor of output. The relationship between the various growth factors is $\gamma_Y = (\gamma_N \gamma_S)^{\frac{1}{1-\alpha}}$. I set $\gamma_Y = 1.0156$, and introduce the parameter χ which indicates the extent to which productivity growth may be attributed to improved processes so that $\gamma_S = \gamma_Y^{(1-\alpha)\chi}$ and $\gamma_N = \gamma_Y^{(1-\alpha)(1-\chi)}$.

The law of motion for capital specifies that $\delta = \frac{I}{K} + 1 - \gamma_Y$. Veracierto (1999) measures the investment-to-capital ratio to be approximately 7.6%, so that δ =9.19%. In turn, the steady state relation $\eta = \frac{\gamma_Y}{1+i}$ pins down the discount factor. Setting $i = 4\%$ as is common in the business cycle literature, η =0.977. I pick ζ so that about 80% of the population is working, which is approximately the US participation rate. I set $\phi = 0.3$, which involves 3% of employment being engaged in managerial activity. This is the approximate proportion of workers employed in managerial occupations in BLS data.

It remains to calibrate $\lambda_1, \lambda_2, \sigma_w^2, \sigma^2, \chi$ and $\kappa,$. These will be closely related to hazard rates, growth rates, investment patterns and cohort effects. Consequently, I used simulated annealing to match these 6 parameters to the following statistics, drawn from Evans (1987), Dunne et al (1988) and Doms and Dunne (1998): the 5-year exit rate, the exit rate for the young (under 5 years of age); the 5-year survivor growth rate, the survivor growth rate among the young; the proportion of investment that is carried out by establishments that are increasing their capital stock by more than 30% ("large investments"), and the proportion of establishments that comprise this investment ("large investors"). The resulting learning and hazard curves are displayed in Figure (4). As can be seen, much of the learning occurs within the first 5-10 years of an establishment's existence, which is consistent with the evidence provided in Evans (1987) and Bakh and Gort (1993). As a result, some episodes of large adjustment will correspond to early growth rather than updating.

Table (3) displays some summary model statistics. The implied plant dynamics are very close to the average dynamics seen in the data, even for statistics that were not explicitly

χ	λ_1	λ_2	σ^2	σ_u^2	κ
66.4%	0.0705	0.0065	0.0620	0.7382	0.3244

Table 2: Parameter Values 2

Statistic	US Data	Model
Working age employed	80%	80%
Plant growth (age 1-6)	45%	47.8%
Survivor growth	35%	30.5%
Relative size (age 1-6 $\div$ mean)	77%	67%
Entrepreneurial employment	3%	3%
New establishments	9.2%	8.6%
5-year exit rate	36%	37%
5-year exit rate, young plants	39%	40%
Large investments	25%	25.5%
Large investors	8%	7.5%
Average age of capital	6.9	7.2
Average establishment age	$\lessapprox 14$	12

Table 3: Summary Statistics

matched. In particular, average age of capital is almost the same as the average age of equipment over the period. Also, average establishment age in the model is about 12 years – average firm age over the period was about 14 years, and average plant age can be expected to be a little lower.

Using large adjustments to identify dates at which the productive process is rearranged, I find that about two-thirds of productivity growth – leading to output growth of 1% per year – can be associated with increases in OC. This is below the 1.75% estimated by Jovanovic and Rousseau (2002) using stock market data, but is bounded above by an overall annual economic growth rate of 1.56%. Moreover, they find that such growth tends to occur in waves, being slower in most periods.

5 Organizational Obsolescence

The mechanism I wish to study is the incompatibility between accumulated learning a and reorganizing the productive process τ after a certain date $t^* = 1973$. Agents wake up in 1973, and hear that their non-tradeable OC will become obsolete if they update thereafter. I refer to this as a *disruptive shock*. The shock is a one-off event, not likely to occur again

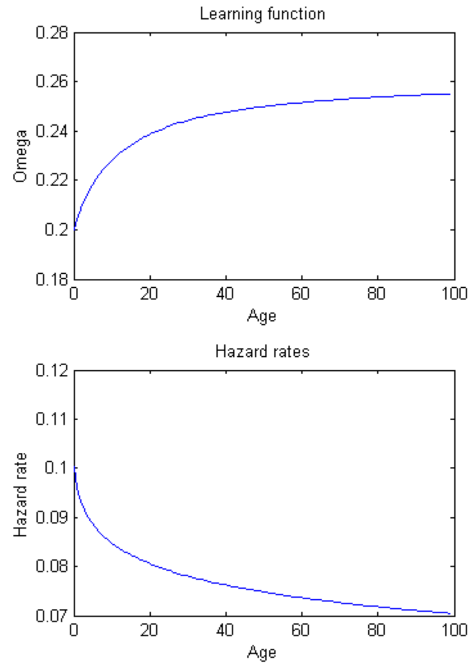

Figure 4: Learning and hazard rates

in the near future. I assume that disruptive shocks are rare and unpredictable[6]. See Table (4) for the mathematical details of the disruption to life-cycle evolution.

There are several interpretations of this shock. It may be that new forms of capital appeared – as in previous accounts – but they were such that their manner of use was sufficiently different that previous experience was no longer applicable. Again, I focus solely on the macroeconomic and asset price dynamics of the learning process, not the nature of the underlying shock.

Establishments may choose not to implement new processes, instead opting to continue accumulating OC that is tied to their old methods until they exit, or until the latter have led them to drop far enough behind frontier processes that they choose to update instead.

The structure of the shock is such that it directly disrupts the establishment's updating rule only once, as OC accumulated on a post-shock process ($\tau_t < t - t^*$) is not disrupted. However, the composition of the economy is disrupted for much longer. Entry and exit ensure that the economy returns asymptotically towards the accommodative steady state.

Note that, after the shock, a will not represent actual establishment age as such, but rather *expertise*, whereas before the shock there was no distinction.

[6]The exercise was repeated with a varying amount of foresight between 5 and 25 years: results were similar, but market clearing at every date was a problem due to the inherent lumpiness of the model.

Current condition t	**Update**	a_{t+1}	τ_{t+1}
Pre-shock	No	$a_{t+1} = a_t + 1$	$\tau_{t+1} = \tau_t + 1$
Pre-shock	Yes	$a_{t+1} = a_t + 1$	$\tau_{t+1} = 0$
Post-shock	No	$a_{t+1} = a_t + 1$	$\tau_{t+1} = \tau_t + 1$
Post-shock, $\tau_t < t - t^*$	Yes	$a_{t+1} = a_t + 1$	$\tau_{t+1} = 0$
Post-shock, $\tau_t \geq t - t^*$	Yes	$a_{t+1} = 0$	$\tau_{t+1} = 0$

Table 4: Evolution of plant types

A few statements about the effects of the shock. First, in partial equilibrium, a disruptive shock leads to adoption delays:

Proposition 2 *Suppose that prices are fixed. Then, for every type, there is a delay in adoption compared to the wait without the shock.*

Proof. The value function is increasing in a. If establishments update, they must go back to $a = 0$. However, prices are fixed so their continuation value has not changed. ■

In general equilibrium, the marginal product of labor decreases after the shock, lowering wages so that Proposition (1) is hard to extend. Regardless, one can show that behavior after the shock differs among cohorts in a systematic manner.

Proposition 3 *After the shock, young establishments update before older ones.*

Consider a plant which has yet to update since the shock. Define its value function at time $t^* + s$ to be $\widetilde{W}\left(s, X_{t^*+s}; a_{t^*}\right)$, where s is the number of periods since t^* and a_{t^*} was its age at time t^*. The option value $\omega(.)$ of organizational capital after s periods is

$$\omega(s, a_{t^*}, X_{t^*+T}) = \max\left\{\widetilde{W}\left(s+1, X_{t^*+s+1}; a_{t^*}\right) - W\left(0, 0, X_{t^*+s+1}\right) - \kappa p\left(X_{t^*+s}\right), 0\right\}$$

Since P is increasing in a_{t^*}, so is $\widetilde{W}$. Older pre-shock incumbents are less likely to exercise the option at any given point in time than younger ones: their opportunity cost is higher. As time goes by, these plants become progressively older, as they age and as the youngest cohorts update first. The young appear more nimble because the old have more to lose in terms of OC, not because they are more nimble as such.

5.1 Results

5.1.1 Output and Productivity

The results are quite striking – see Figure (5). Output remains below trend until after 2000, while GDP growth drops sharply, remaining below its steady state value until 1982, overshooting somewhat to settle down again as the economy returns to the original growth

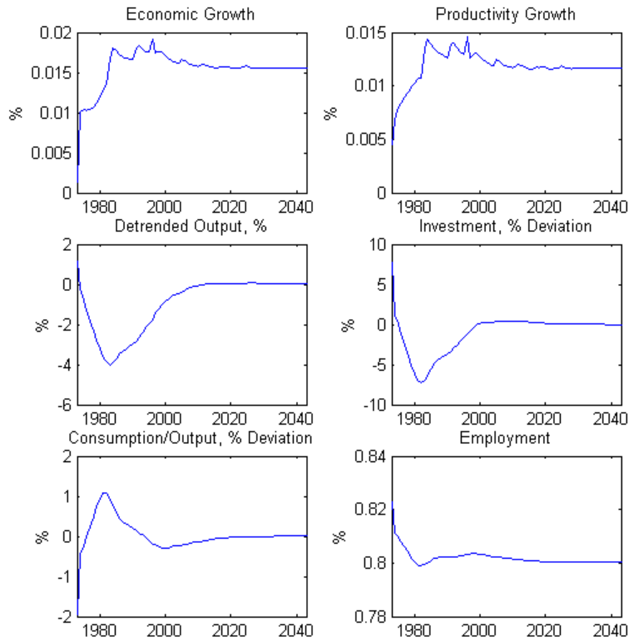

Figure 5: Output and its components

path. Note that the shock does not have a long term effect on the growth path. There is a *temporary deviation* from trend. The deviation lasts far longer than that normally associated with business cycles, and is commensurate with that associated with periods of depression.

While all components of output decline, it is interesting to note that investment suffers more than consumption. Indeed, the share of consumption in output *rises*, a prediction consistent with the findings of Hobijn and Jovanovic (2001). This is the result of consumption smoothing: TFP remains below trend for over 20 years, so investment growth is stunted. The marginal product of capital drops over the period, although its deepest trough is at 97.6% of the steady state value. Throughout the OECD, Orr et al (1995) find that real interest rates decreased in the 1970s, which is broadly in accordance with the model.

When the shock hits, establishment composition is predetermined at their stationary distribution. After the shock, the option value of accumulated OC is high enough that no incumbents update – see Figure (6)). Indeed, updating freezes until 1981. This heralds the advent of the recovery – however, output and productivity remain below trend for longer, as updating entails an aggregate loss of learning.

Eventually, some cohorts of incumbents begin to update, at the cost of OC. Others

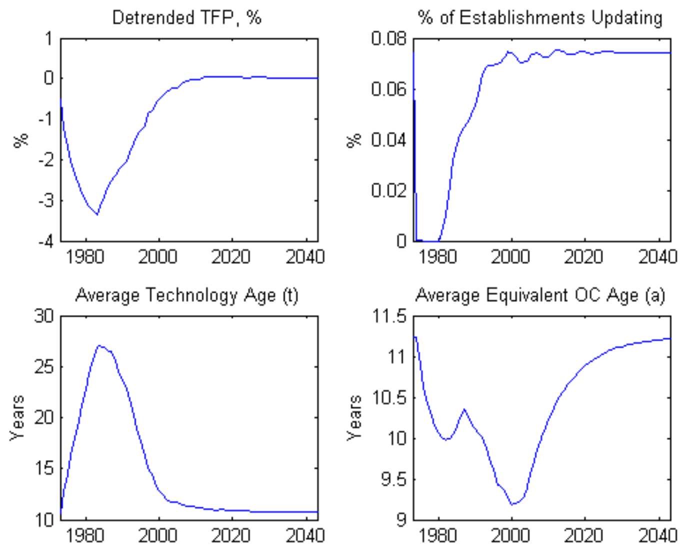

Figure 6: Productivity and its determinants

do not, as they may have accumulated much learning over their lifespans and prefer not to use frontier technologies just yet as in Proposition 2: they climb the learning curve while the underlying productivity of the process they use does not improve. As a result, aggregate TFP growth slows sharply. New entrants and incumbents who have updated find themselves at the early, rapid stages of the learning process. This buoys productivity during the depression and results in TFP growth being high once most establishments have updated (or been washed out by entrants). The shape of the learning curve and the rate of entry dictate dynamics in this stage of the transition.

5.2 Heterogeneity

After the shock hits, new establishments have an unexpected advantage over their incumbent competitors, which will not update in the imminent future due to the concomitant loss of OC. This is reflected in cohort dynamics and asset prices – see Figures (7) and (10). This intergenerational advantage persists, so that entry remains above trend for much of the transition. There is also an increase in exit rates, as there is a relatively high proportion of young establishments. Both these predictions are borne out by the data – see Davis et al (1996). Although the model is not constructed to match rates of job creation and destruction – for which another dimension of heterogeneity would be necessary – Figure (8) shows that the same is true for these statistics. The reversal in exit rates around 1990 is because plant mass and the mass exiting do not synchronize perfectly.

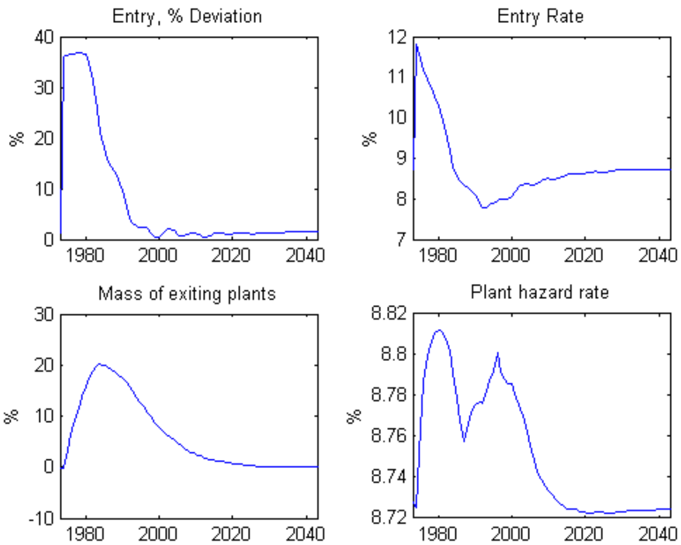

Figure 7: Differential cohort dynamics

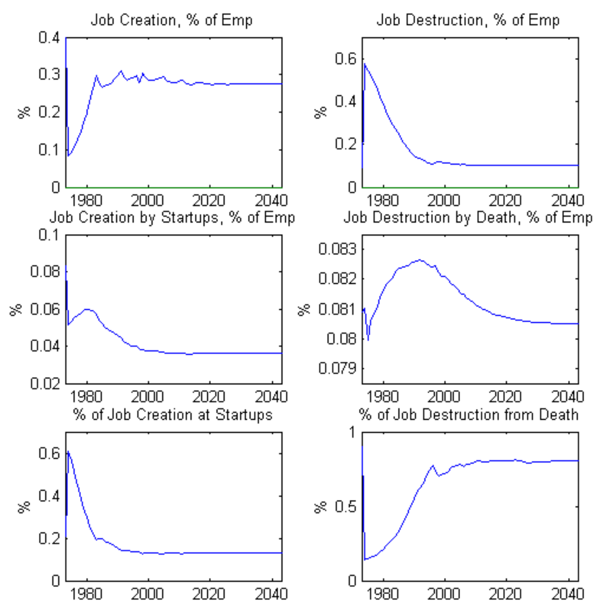

Figure 8: Job flows

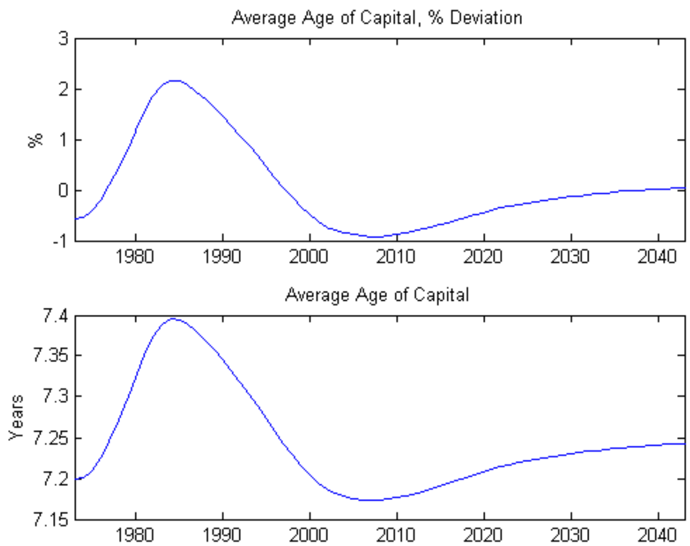

Figure 9: Average age of capital

5.3 Average Age of Capital

Figure (9) shows that the behavior of the average age of capital is consistent with the data, following the dynamics of detrended investment. Average age continues to grow until the late 1980s, decreasing below trend and eventually returning. The peak is a little early, and the magnitude of this change is less than that displayed in the data however. This is becaue the model generates a trough in detrended investment around -5%: in the data detrended investment collapses to -20%. Nevertheless, the model is able to capture qualitatively a rise that contradicts other models. If the model included explicit adjustment costs – either direct or temporal, such as "time-to-build" or "time-to-reorganize" – then the response of investment would be even larger and the delay even longer.

The main criticism of Comin (2001) against the GPT approach to the slowdown is that industries in which computer adoption was commonplace were those in which TFP tended to increase rather than stagnate. In the current model, all establishments, old and new, purchase new equipment when they invest positively, and it is the most productive that invest the most. Those that stagnate as they reorganize their productive process and lose OC invest less until they begin to climb the learning curve again. While climbing the learning ladder, they invest heavily in new capital. Hence, this feature can be driven driven by establishment and aggregate TFP inherent in factors other than capital.

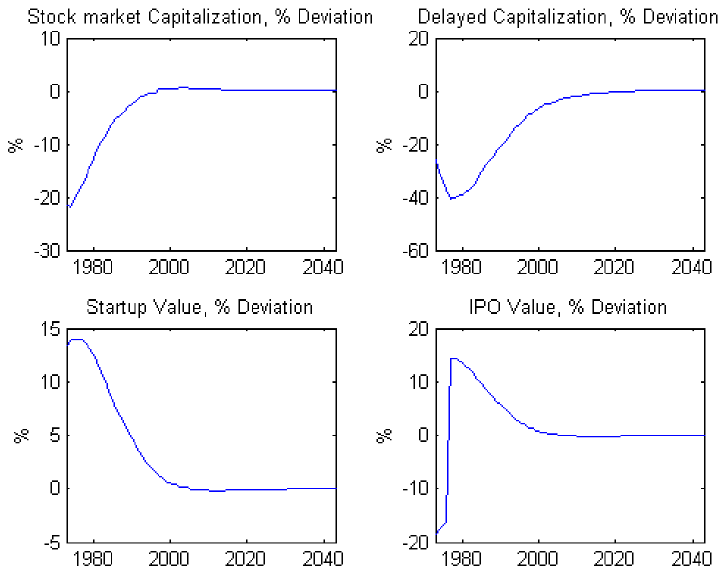

Figure 10: Asset price dynamics

5.4 Asset Prices

This entire time, long term establishment value has been decreasing on average, leading to the stock market dynamics seen in Figure (10). Stock market capitalization shows broadly similar dynamics to those of the US economy in the late 1970s. US capitalization dropped by 40%, not recovering its previous level until around 1994. Model capitalization decreases by 23%, and by 1994 still remains about 4% below its stationary value. This is in spite of the fact that startups are unusually valuable over the transition, and that the number of operating establishments increases.

Thus, in contrast to the account of Hobijn and Jovanovic (2001) that relies on delayed IPOs by the new to generate a stockmarket downturn, the present model generates the downturn *in spite* of the fact that IPO values are increasing over the entire transition and buoying market value. They measure a "time-to-list" lag to be between 1 and 6 years during most of the 1970s, with the lag increasing over the period. If there is a 3 year lag, the stock market drops by 34%, and a 4-year lag leads to a drop in capitalization of 41%. Hence, their insight allows the model to fully match the depth of the stockmarket crunch.

The value of an IPO – assuming a 4-year "time to list" lag – increases over the transition, after a severe initial dip for what are essentially pre-shock incumbents who were approaching their first updating opportunity at the time that the shock hit.

Gordon (1999) finds that, towards the end of the slowdown, productivity in manufacturing outside the IT sector remained depressed throughout the 1990s, and Hobijn and

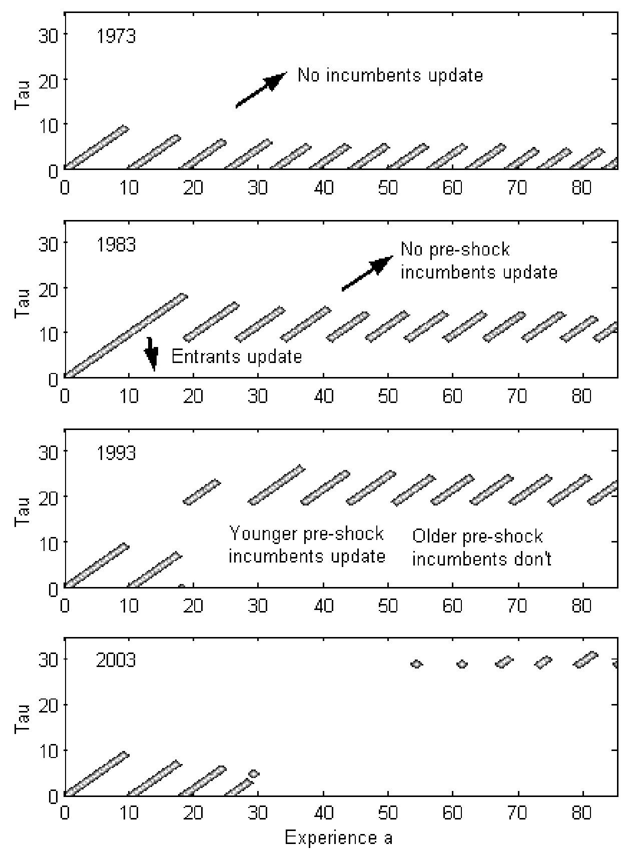

Figure 11: Evolution of establishment life-cycles

Jovanovic (2001) find that the stockmarket recovery was largely due to new entrants. Figure (11) sheds some light on the potential reasons behind this dispersion.

The first panel shows the (τ, a) pairs for which there exists a positive mass of plants, echoing the life-cycle dynamics in Figure (3) – arrows indicate the movement of incumbents between panels. The second panel shows that, after 10 years, the 1973 incumbents have not updated, and post-shock entrants are still to young to have found any benefit in doing so. In the third panel, by 1993 some of the post-shock entrants have updated, as represented by the second diagonal rib along the x-axis. Pre-shock incumbents, however, have yet to update. Finally, by 2003 some of the pre-shock incumbents have updated, and the lifecycle dynamics of post-shock incumbents are essentially back to normal. Pre-shock incumbents have mostly updated at this point, and those who remain are using very outdated processes.

The model contains no sectoral distinctions as such. However, to the extent that the IT and computer sectors have been growing over time (and that entry has become more and more directed towards that sector), the cross-sectional predictions of the model should coincide with Gordon's (1999) cross-sectoral observations.

6 Conclusion and Extensions

I argue that the aggregate dynamics of organizational capital associated with drastic technical change can account for much of the magnitude and persistence of the productivity slowdown, net of any other aspects that such a shock might entail. The model accounts for cross-cohort establishment experiences, and explains a third of the observed changes in investment and average capital age. I am agnostic as to the ultimate origin of the shock, but rather assume as is widely believed that it had technological *implications*, and study the propagation of the shock through the obsolescence of OC. In particular, whether the oil price hike, uncertainty, or some shock directly related to IT was responsible is not addressed – but the propagational effects are so large that it may be difficult to identify. Nonetheless, since a necessary condition for a disruptive shock is a substantially $different$ technology, I interpret the model as supporting an important propagational role for IT.

What factors might increase the investment effect? For a start, the direct effect of that shock might have contributed to the slump. Also, in the model, there is a lower bound on the amount of learning that can be lost. A new, drastically different technology may be sufficiently ill-understood that its manner of implementation is unknown to all, so there is no market for implementation services and establishments must accumulate it via trial and error. This would increase the option value of old organizational capital, delay adoption even further, increase the OC loss when adoption finally takes place, prolonging and deepen the transition.

Also, trend growth is exogenous in the model. If it is in fact endogenous, then trend growth itself might slow down during transition, leading to a deepening and lengthening. Finally, policy may prolong episodes of stagnation (see Prescott (2002)). If agents are rational, policy failures over a particular period must be interpreted in the light of changes in the incentives faced by various constituencies. Since it is the incumbent majority which stands to lose from disruptive shocks, it is only natural that the political process should lead to policies that delay adoption of the new.

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A Learning and Signalling

This section outlines the signalling interpretation of the learning curve, similar to Jovanovic and Nyarko (1996). Each period there is a continuum of managerial inputs (“decisions”) $j \in [0,1]$. The productive process is characterized by a value $\overline{\theta}_j \in \Re$ for each decision dimension j, that is drawn from a normal distribution with known mean[7] and standard deviation σ^2. Let $\overline{\theta} : [0,1] \rightarrow \Re$ be the collection of $\overline{\theta}_j$.

For each j, for each date a, establishments must make a decision $q_{ja} \in \Re$ that is an input into the production process. Let θ_{ja} represent the optimal choice, which is specific to $j \in [0,1]$ and also to the period a. The exact value of θ_{ja} is, however, unknown until after the decision has been made. Let $\overline{\theta}_j$ be the (unknown) mean value of θ_{ja}. Then,

$$\begin{aligned} \theta_{ja} &= \overline{\theta}_j + u_{ja},\ u_{ja}\tilde{\ }N(0,\sigma_u) \\ \rho(u_{ja},u_{js}) &= 0, s \neq a,\ \rho(u_{ja},u_{kt}) = 0, k \neq j \end{aligned} \tag{6}$$

There is a payoff function $\pi(q_{ja},\theta_{ja})$ that depends on both the target and the assay:

$$\pi(q_{ja},\theta_{ja}) = \left(1 - (\theta_{ja} - q_{ja})^2\right)$$

[7] The exact value of the mean will be irrelevant for payoffs and for this reason it is ignored henceforth.

The plant learns from observing the ex-post realizations of θ_{ja} over time. Given the assumption of normal disturbances, at any given date, the information set relevant for dimension j can be represented as the prior variance over $\overline{\theta}_j$, denoted σ^2_{ja}.

The establishment is risk-neutral, so it will always select $q_{ja} = E[\theta_{ja}|\sigma^2_{ja}] = E\left[\overline{\theta}_j|\sigma^2_{ja}\right]$. Then, the realized payoff π^* becomes

$$\pi^*(q_{ja}, \theta_{ja}) = \left(1 - (\theta_{ja} - E\left[\overline{\theta}_j|\sigma^2_{ja}\right] + u_{ja})^2\right)$$

If at time t a plant's prior over $\overline{\theta}_j$ is normal with variance σ^2_{ja}, then after observing θ_{ja} Bayes' rule yields *posterior* variance $\psi(\sigma^2_{ja}) \equiv \frac{\sigma^2_u \sigma^2_{ja}}{(\sigma^2_u + \sigma^2_{ja})}$. If there is no disruption, in that $\overline{\theta}_j$ remains the same, the information set next period $\sigma^2_{j,a+1}$ is then characterized by $\sigma^2_{j,a+1} = \psi(\sigma^2_{ja})$. At the moment that an establishment is born, it is characterized by an information set $\sigma^2_{j0} = \{\sigma^2\}\,\forall j$, where σ^2 is the unconditional variance of $\overline{\theta}_j$.

Let $\Omega(a) \equiv \int_{[0,1]} \pi(q_{ja}, \theta_{ja})dj$ be the aggregation over decisions. The reduced-form learning function is then the solution to the following difference equation:

$$\begin{aligned} \sigma^2_{j0} &= \sigma^2,\, \sigma^2_{j,a+1} = \psi(\sigma^2_{ja}) \forall a \geq 1 \\ \Omega(a) &= E\left[\pi(q_{ja}, \theta_{ja})|\sigma^2_{ja}\right] = 1 - (\sigma^2_{ja} + \sigma^2_u) \end{aligned}$$

This formulation of OC is open to any learning-based interpretation of the notion of OC, so long as the object of learning is the strategy space per se: the "how" rather than the "what". Consider an assignment problem between capital and workers with idiosyncracies. Productivity then depends on signals that managers receive regarding match quality. Since the establishment manages a continuum of inputs, the space of possible assignment strategies has the same cardinality as the real line, and as the set of functions $\overline{\theta} : [0,1] \to \Re$. Thus I model the information structure in the manner of equation (5), applying the appropriate homeomorphism and concentrating on the properties of $\overline{\theta}$ and θ_a. I interpret this as a "reduced form" approach. As for the disruptive shock, an incumbent's information set in case of updating becomes $\sigma^2_{j0} \forall j$.

B Proofs

Proof of Proposition ??. That W exists, is decreasing and convex in τ and increasing and concave in a is immediate from standard recursive methods. That W is decreasing in τ and that U does not depend on τ implies that Υ is increasing in τ, so that the updating rule is of the (S, s) form. Finally, increasing a increases $W(0, a, X_t)$ more than it does $W(\tau, a, X_t)$ for any $\tau > 0$, so that $W(\tau + 1, a, X_t) - U(a, X_t)$ is decreasing in a. Hence, Υ is increasing in a. These two results prove that the policy is (S, s).

As you increase a, this latter decrease becomes *steeper* in τ. This is because the increase in τ in $U(a, X_t)$ is independent of τ, whereas that in $W(\tau+1, a, X_t)$ is decreasing in τ. ■

Proof of Proposition 2. Let a_{t^*} be the age of a plant at the time of the shock. If it has yet to update, its deflated payoff $\widetilde{W}$ is

$$\begin{aligned} \widetilde{W}(T, X_{t^*+s}; a_{t^*}) &= \max_{k_t,n_t}\left\{\gamma^{-s}\Omega(a_{t^*}+s)k_t^{\alpha}n_t^{\beta} - k_t r(X_{t^*+s}) - n_t w(X_{t^*+s})\right\} \\ &\quad +\eta\max\left\{\widetilde{W}\left(s+1, X_{t^*+s+1}; a_{t^*}\right), W\left(0,0,X_{t^*+s+1}\right) - \kappa p\left(X_{t^*+s}\right)\right\} \\ X_{t^*+s+1} &= \Gamma(X_{t^*+s}) \end{aligned}$$

where s is the date of the shock. Note that $\widetilde{W}$ is the fixed point $f = Bf$ of the functional

$$\begin{aligned} Bf(s, X_{t^*+s}; a_{t^*}) &= \max_{k_t,n_t}\left\{\gamma^{-s}\Omega(a_{t^*}+s)k_t^{\alpha}n_t^{\beta} - k_t r(X_{t^*+s}) - n_t w(X_{t^*+s})\right\} \\ &\quad +\eta\max\left\{f\left(s+1, X_{t^*+s+1}; a_{t^*}\right), W\left(0,0,X_{t^*+s+1}\right) - \kappa p\left(X_{t^*+s}\right)\right\} \\ X_{t^*+s+1} &= \Gamma(X_{t^*+s}) \end{aligned}$$

where B is the Bellman operator, and which can be shown to exist via Blackwell's theorem. Given s and t, if f is increasing in a_{t^*} then so is Bf, showing that $\widetilde{W}$ must be: the opportunity cost of updating is increasing with age – whereas $W(0,0,X_{t^*+s+1}) - \kappa p(X_{t^*+s})$ does not. Thus if plants of age a update in a given period, then younger ones would also. ■

C Simulation

Let time $t = 1974$ be the period of shock impact: agents wake up in 1973 and find out that their non-tradeable OC will become obsolete if they update. μ_{1973}, E_{1973} and k_{1973} are already given. If the economy eventually returns to its original state, there should be a date $\widehat{T}$ such that $\mu_{\widehat{T}}$, $E_{\widehat{T}}$ and $K_{\widehat{T}}$ deviate negligibly from their steady state values in their respective spaces. $W(.,.,X_{\widehat{T}})$ will also deviate negligibly from its steady state value, as will decision rules and consequently p, r, w and Γ. I set $\widehat{T} = 2073$.

Given a guess for the wage stream for $t \in \left\{1973, ..., \widehat{T}\right\}$, the rental rate stream[8], value functions for all periods and decision rules can be computed via backward recursion parting from $W(.,.,X_{\widehat{T}})$ and using the first order conditions. These decision rules in turn allow the measure to be computed recursively *forwards* from μ_0. Imposing the law of motion for aggregate capital that is implied by the plant decision rules, household consumption and labor supply rules are derived. A new candidate wage stream is generated until the labor market clears in all periods.

[8]The value of r_0 is set to equate demand and supply of capital in the period after the shock.