News Shocks and Costly Technology Adoption*

Yi-Chan Tsai†

November 10, 2009

Abstract

I study the macroeconomic response to news of future technological innovation under the assumption that firms cannot frictionlessly shift from existing capital stocks to new varieties associated with the impending advance in technology. Combining this new element with variable capital utilization and preferences designed to minimize wealth effects on labor supply, I develop a model that simultaneously accounts for four stylized facts: (1) slow diffusion of new technologies, (2) lumpiness in microeconomic investment, (3) stock prices leading measured productivity, and (4) comovement of consumption, investment and labor hours. On news of a coming technological innovation, firms begin to invest in new capital goods which will allow them to benefit from the innovation once it arrives. Because fixed costs lead some to delay adoption, there is slow diffusion of the new technology. At the firm level, investment in new technology follows an (S, s) rule, and at the aggregate level the model generates a hump-shaped investment pattern typical of the data. Moreover, the introduction of new capital causes the price of old capital to fall, leading stock prices to rise on news of the new technology. Finally, variable capital utilization slows the onset of diminishing returns to labor, so that work hours rise instantly, permitting rises in both consumption and investment.

JEL E32, O33

Keywords: Endogenous Technology Adoption, Business Cycles, News Shocks

*I am indebted to Aubhik Khan, Julia Thomas and Bill Dupor for valuable advice and support, as well as Paul Evans, Masao Ogaki, Nan Li, Belton Fleisher, Pok-Sang Lam, Yuko Imura, Tamon Takamura, Seungho Nan, Kerry Tan, Andreas Schick, and Michael Sinkey for helpful discussions. All errors are my own responsibility.

†Department of Economics, The Ohio State University, 410 Arps Hall, 1945 N. High Street, Columbus, OH 43210 *Email address*: tsai.181@osu.edu

1 Introduction

Macroeconomics has witnessed a revival of interest in expectations-driven business cycles in recent years, motivated in part by the information-technology-related investment boom of the 1990s. A body of empirical evidence has shown that, following a positive news shock, households and firms increase both consumption and investment in anticipation of future technological innovation.[1] Furthermore, if the anticipated technological improvement later fails to meet expectations, consumption and investment will fall, generating a recession. Because this type of boom-bust cycle can occur without technological regress, many have argued that news about future productivity improvements may be an important source of business cycle fluctuations.

Unfortunately, when researchers incorporate news shocks into standard dynamic stochastic general equilibrium models, the resulting model predictions are at odds with both the mechanisms and the empirical evidence outlined above. In particular, while consumption increases in response to a positive news shock, investment is predicted to decrease. This problem arises because labor, and thus output, does not rise in response to the shock, so any rise in consumption must come at the expense of investment.

Recognizing the problem above, several recent papers have incorporated various mechanisms into standard models to stimulate positive labor and investment responses to positive news, and thus develop more successful models of boom-bust cycles. Leading examples include Beaudry and Portier (2004), Christiano, Ilut, Motto, and Rostagno (2007) and Jaimovich and Rebelo (2008). Each of these models succeeds in generating positive comovement between consumption and investment. However, each also assumes that capital goods acquired at different times are perfect substitutes in production, despite empirical evidence that capital productivity is specific to a particular technology. Furthermore, in almost every existing model designed to reconcile the idea of boom-bust cycles with observed business cycles, the assumption of convex investment adjustment costs plays a vital role in stimulating coincident rises in labor, consumption and investment on the arrival of positive news. Although convex adjustment costs may have desired effects in the aggregate, they are known to be inconsistent with microeconomic investment patterns.[2]

[1] Schmitt-Grohe and Uribe (2008) estimate the contribution of anticipated technology shocks to business cycles in the postwar United States using a Bayesian method. They find that output, consumption, investment and labor all increase in response to anticipated shocks, and these shocks explain more than two thirds of aggregate fluctuations. Similarly, Beaudry and Portier (2006) show that consumption, investment and labor hours all rise in response to an anticipated technology shock, as identified by a vector error correction model. Their study isolates anticipated shocks as the source of roughly one half of business cycle fluctuations.

[2] Because convex adjustment costs encourage firms to smooth any single investment project over many periods, they rule out the large and occasional (or lumpy) investment activities observed in various establishment-level studies. Using U.S. manufacturing data, Doms and Dunne (1993) and Cooper, Halti-

I develop a general equilibrium vintage capital model wherein (a) technological progress is capital-embodied and (b) firms can replace capital of one vintage with capital of a newer vintage only upon payment of fixed adoption costs. I treat a news shock as information of a coming large technological innovation that will require costly technology adoption to be useful.[3] Following news of a technological leap, because such large advances are capital embodied, firms understand that they must purchase a new type of capital to realize any productivity benefit. More specifically, firms cannot benefit by simply purchasing more of their existing variety of capital, but instead must acquire the capital designed for the new technology. Next, I assume that firms must pay fixed adoption costs in order to replace their existing capital with new-vintage capital. Given idiosyncratic differences in adoption costs, this microeconomic friction leads to gradual technology adoption in the aggregate. Firms encountering low adoption costs upgrade their capital immediately, while firms facing higher current costs delay adoption to a later date. As a result, a new technology diffuses slowly, and different vintages of capital can coexist for an extended time following news of a coming technology advance. Moreover, at the firm level, investment in new technology follows an (S,s) rule, while the model generates a hump-shaped aggregate investment pattern typical of the data, (see Christiano, Eichenbaum and Evans (2005)).

I combine the technology diffusion mechanism described above with two elements routinely adopted in the news shock literature to encourage an immediate labor supply response (variable capital utilization and preferences with minimal wealth effects on labor supply) and examine whether my resulting model of technology adoption generates the desired comovement between consumption, labor hours, and investment following a news shock. I find that the model not only succeeds in this respect but also succeeds with regard to three additional stylized facts commonly missed by news shock models: the slow diffusion of new technologies, the lumpiness in microeconomic investment, and the fact that stock prices lead measured productivity.

One interesting feature of my model is the endogenous determination of the price of old capital relative to that of new capital. Because only new capital can be used effectively with a new technology, old capital is not perfectly substitutable for new capital. As a result, the resale price of old capital drops below the unit purchase price of new capital following a

wanger and Power (1999) document that lumpy investment episodes represent a large fraction of a typical establishment's cumulative capital adjustment over time. Moreover, within a typical year, roughly one-quarter of aggregate investment arises from the activities of establishments exhibiting investment spikes. Most importantly, in terms of cyclical changes, these studies uncover a strong positive correlation between aggregate investment and the number of establishments exhibiting spikes.

[3] In the absence of a news shock, technology changes are small, ongoing improvements of the standard variety. In such times, firms frictionlessly adjust their capital stocks to offset the effects of physical and economic depreciation.

positive news shock. This fall in the relative price of old capital implies a drop in replacement costs, which leads stock prices to rise at the impact of the shock.

There is substantial evidence of capital embodied technological progress consistent with the framework I adopt. Greenwood, Hercowitz, and Krusell (1997) report that an efficiency increase in capital due to improved technology can account for a substantial portion of output growth in the postwar U.S. In particular, they argue that the decline in the relative price of equipment in the postwar era, alongside the rising ratio of equipment to GDP, is evidence of technological progress in equipment production.[4] Bahk and Gort (1993) study micro-level data on output and capital vintage from more than 2000 firms across 41 industries and find that a one year change in the average age of capital is associated with a 2.5%-3.5% change in output.[5] In addition, historical studies such as Devine (1983) document that, after the Second Industrial Revolution, manufacturers found it necessary to build new firms in order to adopt new technology based on electricity. Similarly, David (1990) argues that "the slow pace of (electricity) adoption prior to the 1920s was largely attributable to the unprofitability of replacing still serviceable manufacturing firms embodying production technologies adapted to the old regime of mechanical power derived from water and steam."

Most technology adoption costs are nonconvex in nature and incurred only when a firm wishes to adjust its technology level. We list two such costs for example. One is capital expenditure associated with technology adoption. The other is organization costs associated with the accumulation of firm-specific knowledge. Even after new capital is acquired, firms still need to learn how to apply the new technology. Since the nature of a new technology differs from the existing technology, its proper use and implementation may require a substantial reorganization of the production process. Schurr et. al. (1990) discuss the process of learning following new applications of electricity to firm and machine design. Similarly, companies that adopted IT did not become more productive without also adopting certain complementary changes in their business organization.

There is also ample evidence in favor of the pattern of technology adoption predicted by my model. Studies such as David (1990) examine dynamic adjustments following technological advances and document that new technology does not immediately accelerate productivity growth but rather diffuses gradually. For example, in the Second Industrial Revolution, the development of electricity did not immediately generate higher productivity; however,

[4] This interpretation also applies to the IT revolution, since substantial high-tech investment accompanied the declining relative price of IT over the past three decades.

[5] Campbell (1998) finds that the entry rate covaries positively with output and total factor productivity growth, and the exit rate leads all three of these. He argues that a vintage capital model with technological progress embodied in new plants is consistent with this evidence. Elsewhere, using measures of obsolescence, Boddy and Gort (1974) find that capital embodied technical change is an important component of productivity growth.

it was followed by a prolonged period of rapid productivity acceleration. Similarly, in the case of the IT revolution, productivity began to accelerate roughly two decades after U.S. businesses had invested in information technology.[6] Atkeson and Kehoe (2001) argue that this delay in productivity increase was caused by the slow diffusion of new technologies as well as the learning process required for firms to effectively use those technologies.

As mentioned above, my paper differs from most studies in the news shock literature in two important ways; it does not rely on convex adjustment costs to gradualize aggregate investment, and it avoids the counterfactual assumption that all capital goods are equally compatible with a new technology. The model most closely related to mine is that of Comin, Gertler, and Santacreu (CGS, 2008), given its emphasis on endogenous technology diffusion following a news shock. Relative to that study, my model is distinguished along three margins. First, CGS assume that any new technology is freely available to all firms once it is successfully adopted by one, and they emphasize the productivity gains arising from the production of a wider variety of intermediate inputs in a monopolistically competitive setting. By contrast, I consider a perfectly competitive environment wherein technology adoption is a costly activity for every firm; a firm's productivity rises with the arrival of a new technology in my model only if that firm has paid to acquire the new vintage of capital compatible with the new technology. Second, I assume that, once a firm pays its adoption cost to purchase new capital, that firm will be able to use the associated new technology with certainty. CGS instead assume that the probability of successfully adopting a new variety of intermediate goods is increasing in the level of final output devoted to technology adoption. This assumption, alongside variable capital utilization, allows output to rise at the impact of a news shock, which is critical in generating the rise in investment in their model. Finally, while the CGS model succeeds in generating co-movement in consumption and investment following a news shock, it delivers gradual rises in output and TFP consistent with the evidence above only with the inclusion of several additional frictions (habit formation in consumption, convex investment adjustment costs and Calvo price stickiness). My model requires no such extension.

The remainder of this paper is organized as follows. In the next section, I develop my general equilibrium model of news shocks with capital embodied technological progress and costly technology adoption. In section 3, I specify the model's functional forms and parameter values. Section 4 displays the transitional dynamics in this economy following a news shock and discusses how these dynamics arise, isolating the role played by each model

[6] This is sometimes refered to as the computer paradox based on Robert Solow's observation during the 1970-1990 period that one could see evidence of the computer everywhere except in the productivity statistics.

ingredient mentioned above. Finally, section 5 concludes.

2 General equilibrium model with technology adoption

I study a general equilibrium vintage capital model embedded with a technology adoption decision. There is new technology of which news arrives T_1 periods in advance. During times of abrupt technological transitions, like the IT Revolution, existing capital goods are no longer perfect substitutes for new capital. Understanding this, firms must decide when to replace their existing capital with new capital. This adoption is not costless; it involves the payment of fixed adoption costs. Given idiosyncratic differences in these adoption costs, both vintages of capital coexist, and new technologies diffuse slowly across firms through their adoption decisions. There are three economic agents in this economy: (1) households, (2) firms that have adopted the new technology, and (3) firms that continue to use the old technology. I describe their optimization problems below following a description of the technological environment.

2.1 Capital-embodied technological process

In period 0, the economy is in an initial steady state and the capital-embodied technology level equals ε_0. In the next period, news arrives that there will be a permanent technology improvement associated with a new type of capital beginning in period T_1. More specifically, agents know that productivity will remain unchanged until the materialization of the new technology and then exhibit a single discrete jump. They also know that each firm must purchase a new vintage of capital in order to benefit from the advance in technology when it arrives.

The new type of capital is compatible with both the new and the old technology, while the old type of capital is compatible with only the old technology. Therefore, the productivity of old capital does not change when the technological advance happens, i.e., $\varepsilon_{0,t} = \varepsilon_0$, $\forall t$. By contrast, the productivity attached to the new capital rises with the arrival of the new technology, as shown below.

$$\varepsilon_{1,t} = \begin{cases} \varepsilon_0 & \text{for} \quad t < T_1, \\ \varepsilon_1 > \varepsilon_0 & \text{for} \quad t \geq T_1 \end{cases} \tag{1}$$

2.2 Firms' optimization problems

I deviate from the standard assumption that capital is homogeneous and instead assume that productivity varies across vintages of capital. I use the subscript $i \in \{0, 1\}$ to identify variables associated with each of the two capital vintages. Specifically, k_0 and ε_0 represent the per-firm stock and the productivity associated with the old vintage of capital. Similarly, k_1 and ε_1 represent the per-firm stock and the productivity of the new vintage. Each firm produces output using its predetermined capital stock, k_i, labor hours, n_i, and capital utilization rates, h_i, via a decreasing returns to scale production function, $zf(\varepsilon_i h_i k_i, n_i)$. Here, z reflects stochastic total factor productivity which is common across firms. I assume that z follows a Markov chain $z \in \{z_1, ..., z_{N_z}\}$, where $\Pr(z' = z_j|\ z = z_i) \equiv \pi_{ij} \geqslant 0$, and $\sum_{j=1}^{N_z} \pi_{ij} = 1$ for each $i = 1, ..., N_z$. Let s represent the distance between date t and the time that news shocks is realized, i.e, $s = max\{T_1 - t, 0\}$. Firms take as given these two exogenous components of the aggregate state, (z, s), as well as the endogenous component, θ, that represents the fraction of all firms that have adopted the new technology.

At any point in time, each firm is distinguished by its capital productivity, ε_i, its predetermined capital stock, k_i, and its current idiosyncratic draw of a fixed cost associated with technology adoption, $\xi \in [\xi_L, \xi_U]$, which is denominated in units of labor. Given the aggregate state of the economy, each firm chooses its current level of employment, its capital utilization rate and its investment.

The investment decision involves a choice of whether to switch from the existing capital (technology) to the new, more efficient capital (technology) or to continue operating with the existing capital. A firm adopting the new capital must pay a one-time technology adoption cost, ξ. This implies the forfeit of $w(z, \theta, s)\xi$ units of current output, where $w(z, \theta, s)$ denotes the real wage rate. Note that these fixed costs do not apply to investment at any time other than the single date in which the firm first adopts the new capital. Therefore, if a firm decides to continue operating with its current vintage of capital, it undertakes frictionless capital adjustment. The firm's capital stock evolves according to $k_i' = (1 - \delta(h_i))\, k_i + i_i$, where i_i is the current investment associated with vintage i and $\delta(h_i)$ is the capital depreciation rate. I assume that depreciation is increasing and convex in the rate of capital utilization; $\delta'(h) > 0$ and $\delta''(h) > 0$.

A firm can operate only one technology at a time. Consequently, every firm in the economy has only one vintage of capital at any date. For firms that have previously adopted the new technology, adoption costs are irrelevant, since I study a single discrete change in technology. Those firms choose employment, n_1, a capital utilization rate, h_1, and a capital stock for the next period, k_1', to maximize their expected discounted profits. The value of any such firm is listed below, with the subscript 1 on the value function indicating that the firm has previously adopted the new capital.

$$
\begin{aligned}
v_1(k_1; z, \theta, s) \quad \equiv \quad & \max_{n_1, h_1, k_1'} \Big(z f(\varepsilon_1 h_1 k_1, n_1) - w(z, \theta, s) n_1 + (1 - \delta(h_1)) k_1 \\
& - k_1' + \sum_{j=1}^{N_z} d_j(z, \theta, s) v_1(k_1'; z_j, \theta', s') \Big)
\end{aligned} \tag{2}
$$

Here, firms discount their next-period expected value by $d_j(z, \theta, s)$ when the current aggregate state is (z, θ, s) and next period's productivity is z_j. The choices of employment and capital utilization rate satisfy the following conditions.

$$
z D_n f(\varepsilon_i h_i k_i, n_i) = w(z, \theta, s) \tag{3}
$$

$$
z D_h f(\varepsilon_i h_i k_i, n_i) = \delta'(h_i) k_i \tag{4}
$$

Equation (3) sets the marginal product of labor equal to the wage. Equation (4) characterizes the efficient capital utilization rate that equates the marginal benefit and marginal user cost of capital services. The marginal user cost of capital is captured by the increased capital depreciation due to higher capital utilization rate. The capital stock k_1' solves the following problem.

$$
g_1(z, \theta, s) \equiv \arg\max_{k_1'} \Big(-k_1' + \sum_{j=1}^{N_z} d_j(z, \theta, s) v_1(k_1'; z_j, \theta', s') \Big). \tag{5}
$$

Firms that have not previously switched to the new technology face an additional decision beyond the choice of employment, capital utilization, and the level of investment. They must decide whether to switch from their existing capital vintage to the new, more efficient capital. As noted above, the replacement of one vintage of capital with another involves a fixed adoption cost, ξ. This adoption cost varies across firms and over time for any given firm. Each period, each firm draws a cost from the time-invariant distribution $G(\xi) : [\xi_L, \xi_U] \to [0, 1]$. Based on that cost, firms decide whether to adopt the new technology.

A firm that has not previously switched to the new technology is identified by its capital stock, k_0, as well as its current technology adoption cost, ξ. Let $e_0(k_0, \xi; z, \theta, s)$ represent the present discounted value of a firm with old capital k_0, and current fixed cost draw ξ. I define its expected value over ξ as $v_0\left(k;z,\theta,s\right)$.

$$v_0\left(k;z,\theta,s\right) \equiv \int_{\xi_L}^{\xi_U} e_o\left(k_0,\xi;z,\theta,s\right) G\left(d\xi\right) \tag{6}$$

With the technology adoption decision, the value of any firm will depend on its binary choice of technology adoption as below.

$$e_0\left(k_0,\xi;z,\theta,s\right) = \max\left(e_0^A(k_0;z,\theta,s) - \xi w(z,\theta,s), e_0^N(k_0;z,\theta,s)\right) \tag{7}$$

Let $q_0(z,\theta,s)$ represent the relative price of the old vintage of capital. Here $e_0^A(k_0;z,\theta,s)$ and $e_0^N(k_0;z,\theta,s)$ solve the optimization problem for a firm that adopts the new technology and that for a firm that does not, respectively.

$$\begin{aligned} e_0^A(k_0;z,\theta,s) \quad \equiv \quad & \max_{n_0,h_0,k_1'}\Big(zf\left(\varepsilon_0 h_0 k_0, n_0\right) - w\left(z,\theta,s\right)n_0 + \left(1-\delta(h_0)\right)k_0 q_0(z,\theta,s) \\ & -k_1' + \sum_{j=1}^{N_z} d_j\left(z,\theta,s\right) v_1\left(k_1';z_j,\theta',s'\right)\Big) \end{aligned} \tag{8}$$

$$\begin{aligned} e_0^N(k_0;z,\theta,s) \quad \equiv \quad & \max_{n_0,h_0,k_0'}\Big(zf\left(\varepsilon_0 h_0 k_0, n_0\right) - w\left(z,\theta,s\right)n_0 + \left(1-\delta(h_0)\right)k_0 q_0(z,\theta,s) \\ & -k_0' q_0(z,\theta,s) + \sum_{j=1}^{N_z} d_j\left(z,\theta,s\right) v_0\left(k_0';z_j,\theta',s'\right)\Big) \end{aligned} \tag{9}$$

If a firm decides to adopt a new technology, it sells all of its existing, old vintage capital after the current period's production and selects a level of new vintage capital with which to enter the next period, k_1'. Firms that continue to use the old technology invest in their existing vintage at the relative price $q_0(z,\theta,s)$.

Let $\hat{\xi}(k_0;z,\theta,s)$ denote the fixed cost that leaves a firm indifferent between adopting and not adopting the new technology.

$$e_0^A(k_0;z,\theta,s) - e_0^N(k_0;z,\theta,s) = \hat{\xi}(k_0;z,\theta,s)w(z,\theta,s)$$

Here, $e_0^A(k_0;z,\theta,s) - e_0^N(k_0;z,\theta,s)$ captures the potential gain from adopting new technologies due to the subsequent productivity gains, and $\xi w(z,\theta,s)$ is the output-weighted fixed adoption cost. I define the *threshold adoption cost* as $\overline{\xi}(k_0;z,\theta,s) = \min\{\xi_U, \max\{\xi_L, \hat{\xi}(k_0;z,\theta,s)\}\}$, so that $\xi_L \leq \overline{\xi}(k_0;z,\theta,s) \leq \xi_U$. Any firm with an adoption cost at or below this threshold cost will pay the cost and adopt the new technology. Firms choosing to adopt will select the same k_1' as is selected by firms that have previously adopted, the solution to (5). Firms that do not adopt choose k_0' to solve the following.

$$g_0(z,\theta,s) \equiv \arg\max_{k_0'} \Big(-q_0(z,\theta,s)\, k_0' + \sum_{j=1}^{N_z} d_j(z,\theta,s)\, v_0(k_0'; z_j, \theta', s') \Big). \tag{10}$$

Given the threshold adoption costs, I can divide firms entering the period with k_0 into two groups. Those firms that draw an adoption cost at or below the threshold cost $\overline{\xi}(k_0,z,\theta,s)$ adopt the new technology. Those drawing costs above the threshold cost, they continue to operate the old technology. Thus, the adoption decision follows an (S, s) rule and the next-period capital stock for firms that have not previously adopted is as listed below.

$$k' = \begin{cases} g_1(z,\theta,s) & \text{if} \quad \xi \le \overline{\xi}(k_0,z,\theta,s), \\ g_0(z,\theta,s) & \text{if} \quad \xi > \overline{\xi}(k_0,z,\theta,s) \end{cases} \tag{11}$$

2.3 Households' optimization problem

There is a representative household that maximizes its lifetime utility by choices of consumption, c, state-contingent bonds, a_j', and labor hours, n. Each state-contingent bond, a_j', is priced by $d_j(z,\theta,s)$, a function of the current aggregate state and future total factor productivity, z_j. Each such bond pays one unit of output contingent on the exogenous realization of next period's aggregate productivity being z_j.[7]

I assume firms are owned by the representative household. Therefore, each period the household receives an aggregate dividend that is the sum of all firms' profits. Let $\pi_1(k_1,z,\theta,s)$ represent the average per-firm profit among firms that have previously adopted, and $\pi_0(k_0,z,\theta,s)$ the average per-firm profit among those that have not. Therefore, the aggregate dividend equals $\pi_0(k_0,z,\theta,s)(1-\theta) + \pi_1(k_1,z,\theta,s)\,\theta$. Also, the household receives wage income for its labor effort.

The household takes as given the evolution of the fraction of firms that have adopted the new technology and the time between now and the news is realized, which evolves according to the equilibrium mapping $\theta' = \Gamma(z,\theta,s)$ and $s' = \Theta(s)$ respectively. Its optimization problem is listed below.

[7] With the representative household, zero-net supply condition for state-contingent bonds should hold in equilibrium.

$$W\left(a_i;z,\theta,s\right)=\max_{c,n_h,\left(a_j'\right)_{j=1}^{N_z}}\left[u\left(c,1-n_h\right)+\beta\sum_{j=1}^{N_z}\pi_{ij}W\left(a_j';z_j,\theta',s'\right)\right] \tag{12}$$

subject to

$$c+\sum_{j=1}^{N_z}d_j\left(z,\theta,s\right)a_j'\leq w\left(z,\theta,s\right)n_h+a_i+(1-\theta)\pi_0\left(k_0,z,\theta,s\right)+\theta\pi_1\left(k_1,z,\theta,s\right)$$

$$\theta'=\Gamma\left(z,\theta,s\right).$$

$$s'=\Theta(s) \tag{13}$$

The household's optimal choices of consumption, hours worked and state-contingent bonds satisfy the following conditions.

$$w\left(z,\theta,s\right)D_1u\left(c,1-n_h\right)=D_2u\left(c,1-n_h\right). \tag{14}$$

$$d_j\left(z,\theta,s\right)=\beta\pi_{ij}\frac{D_1u\left(c_j',1-n_{hj}'\right)}{D_1u\left(c,1-n_h\right)}, \tag{15}$$

2.4 Market clearing

Output produced by both types of firms can be used either for consumption or investment in either type of capital. Therefore, goods market clearing requires:

$$c+q_0I_0+I_1=\theta zf\left(\varepsilon_1h_1k_1,n_1\right)+(1-\theta)zf\left(\varepsilon_0h_0k_0,n_0\right) \tag{16}$$

where I_0 is newly produced old capital and I_1 is newly produced new capital. The market clearing condition for the old vintage of capital is

$$I_0=(1-\theta)[(1-G(\overline{\xi}\left(k_0,z,\theta,s\right)))k_0'-(1-\delta(h_0))k_0] \tag{17}$$

The righthand side of equation (17) represents the net demand for investment in old vintages which equals overall demand for investment in old capital from those who have not switched minus the supply of old capital from those have switched in the current period. If $q_0<1$, households would never forgo a unit of consumption for investment in the old vintage and therefore $I_0=0$. The supply of old capital will then equal the undepreciated capital stock of those who decide to adopt the new technology. If $q_0=1$, in addition to the undepreciated old capital, new units of the old vintage will be produced to satisfy the demand of those who continue operation of the old technology.

The market clearing condition for the new vintage of capital is as below.

$$I_1 = G(\bar{\xi}\,(k_0, z, \theta, s))(1-\theta)k_1' + \theta(k_1' - (1-\delta(h_1))k_1) \tag{18}$$

The supply of new capital comes from the newly produced frontier capital, and the demand comes from both those that have adopted the new technology previously and those that adopt in the current period. This implies investment in new capital along both the intensive and extensive margin.

Labor market clearing requires the following condition be satisfied.

$$n_h = (1-\theta)\, n_o + \theta n_1 + (1-\theta) \int_{\xi_L}^{\bar{\xi}} \xi G(d\xi) \tag{19}$$

Given the adoption cost's cumulative distribution function, G, and the threshold, $\bar{\xi}$, I can characterize the law of motion for θ, the fraction of firms operating the new technology as follows.

$$\theta' = \left[G\left(\bar{\xi}\,(z, \theta, s)\right)(1-\theta) \right] + \theta \tag{20}$$

The measure of firms operating with new capital next period is the sum of all firms that operated with new capital this period together with those that adopted the new technology this period, having drawn adoption costs not exceeding the threshold ξ.

Finally, the law of motion for s, the time distance between the current period and the period when news is realized is defined as below.

$$s' = \max\{s-1, 0\}$$

2.4.1 Recursive competitive equilibrium

A *recursive competitive equilibrium* is a set of functions $(w, v_0, v_1, (a_j)_{j=1}^{N_z}, c, n^h, \{g_i, n_i, h_i\}_{i=0}^{1},$ $(d_j)_{j=1}^{N_z}, w, \pi_0, \pi_1, \Gamma)$ such that

1. W solves (12) and $\left(c, n_h, (a_j)_{j=1}^{N_z}\right)$ are the associated optimal policies.

2. v_0 and v_1 solve (2) and (6) - (9) and $\{g_i, n_i, h_i\}_{i=0}^{1}$ are the associated optimal policies.

3. Markets for output, employment and state-contingent bonds clear, satisfying (16)-(19) and the following zero-net supply condition.

$$a_j\,(0, z, \theta, s) = 0, \text{ for } j = 1, \ldots, N_z. \tag{21}$$

4. Aggregate and individual decisions are consistent, Γ is defined by (20) while average per-firm profits among firms that have previously adopted, $\pi_1(k_1, z, \theta, s)$, and average per-firm profits among those that have not, $\pi_0(k_1, z, \theta, s)$ are as follows.

$$\pi_1(k_1, z, \theta, s) = zf(\varepsilon_1 h_1 k_1, n_1) - w(z, \theta, s) n_1 + (1 - \delta(h_1)) k_1 - k_1' \tag{22}$$

$$\begin{aligned} \pi_0(k_0, z, \theta, s) = {} & zf(\varepsilon_0 h_0 k_0, n_0) - w(z, \theta, s) n_0 - w(z, \theta, s) \int_{\xi_L}^{\bar{\xi}} \xi G(d\xi) \\ & - \left(1 - G\left(\bar{\xi}\right)\right) g_0(z, \theta, s) q_0(z, \theta, s) - G\left(\bar{\xi}\right) g_1(z, \theta, s) \\ & + (1 - \delta(h_0)) k_0 q_0(z, \theta, s) \end{aligned} \tag{23}$$

2.5 A convenient reformulation of firms' problems

If I define $p(z, \theta, s)$ as the households' marginal valuation of consumption, i.e., $p(z, \theta, s) = D_1 u(c, 1 - n_h)$, and use $p(z, \theta, s)$ to value firms' current profit, I can reformulate firms' value functions in units of marginal utility as below, eliminating the state-dependent discount factors, without loss of generality. For those firms that have previously adopted, I have:

$$\begin{aligned} V_1(k_1; z, \theta, s) \equiv {} & \max_{n_1, h_1, k_1'} \Big(\left[zf(\varepsilon_1 h_1 k_1, n_1) - w(z, \theta, s) n_1 + (1 - \delta(h_1)) k_1 \right] p(z, \theta, s) \\ & - p(z, \theta, s) k_1' + \beta \sum_{j=1}^{N_z} \pi_{ij} V_1(k_1'; z_j, \theta', s') \Big) \end{aligned} \tag{24}$$

For firms that have not adopted in the past, the problem becomes:

$$V_0(k; z, \theta, s) \equiv \int_{\xi_L}^{\xi_U} E_o(k_0, \xi; z, \theta, s) G(d\xi) \tag{25}$$

where

$$E_0(k, \xi; z, \theta, s) = \max\left(E_0^A(k_0; z, \theta, s) - \xi w(z, \theta, s) p(z, \theta, s), E_0^N(k_0; z, \theta, s)\right)$$

and $E_0^A(k_0; z, \theta, s)$ and $E_0^N(k_0; z, \theta, s)$ are defined as below.

$$\begin{aligned} E_0^A(k_0; z, \theta, s) \equiv {} & \max_{n_0, h_0, k_1'} \Big(\left[zf(\varepsilon_0 h_0 k_0, n_0) - w(z, \theta, s) n_0 + (1 - \delta(h_0)) k_0 q_0(z, \theta, s) \right] p(z, \theta, s) \\ & - p(z, \theta, s) k_1' + \beta \sum_{j=1}^{N_z} \pi_{ij} V_1(k_1'; z_j, \theta', s') \Big) \end{aligned} \tag{26}$$

$$
\begin{aligned}
E_0^N\left(k_0; z, \theta, s\right) \equiv \max_{n_0, h_0, k_0'} \Big(& \left[zf\left(\varepsilon_0 h_0 k_0, n_0\right) - w\left(z, \theta, s\right) n_0 + \left(1 - \delta(h_0)\right) k_0 q_0\left(z, \theta, s\right)\right] p\left(z, \theta, s\right) \\
& - k_0' q_0\left(z, \theta, s\right) p\left(z, \theta, s\right) + \beta \sum_{j=1}^{N_z} \pi_{ij} V_0\left(k_0'; z_j, \theta', s'\right) \Big)
\end{aligned} \tag{27}
$$

3 Functional Forms and Parameter Values

Following the arrival of the new technology, there are two possible steady states, one in which the new technology fails to compete with the existing technology, and the other where the new technology is fully adopted by firms. If the fixed adoption costs are relatively expensive, the new technology may fail to spread across firms. Conversely, if the technology adoption is relatively cheap, the new technology will eventually spread across the firms.

The parameters, ε_1, ε_0, ξ_U, and ξ_L, are especially important in determining whether the first or the second steady state will arise. In the following discussion, I will focus on the second steady state, in which the new technology will spread across firms. I assume the following functional forms for calculating the steady states as well as for the numerical simulation. The production function takes the following Cobb-Douglas form: $zf\left(\varepsilon hk, n\right) = z\left(\varepsilon hk\right)^{\gamma} n^{\nu}$. The depreciation rate function is increasing in capital utilization rate where $\delta(h) = \delta_0 + \delta_1 h^{1+\eta} \diagup (1+\eta)$. I use the utility function proposed by Greenwood, Hercowitz, and Huffman (1998, hereafter GHH) where $u\left(c, 1 - n_h\right) = \left(c - \psi n_h^{1+\rho} \diagup (1+\rho)\right)^{1-\sigma} \diagup (1-\sigma)$. GHH preferences have the property that labor hours is only affected by the substitution effect and is independent of the wealth effect. Finally, I choose a uniform distribution function for the time invariant distribution with respect to the technology adoption costs.

In the full adoption steady state, aggregate output, consumption, investment, labor hours and productivity all are higher than their old steady state values. The increased capital productivity leads to a higher capital stock. With the higher capital productivity, the return to labor will increase, and therefore the real wage and labor hours will increase as well. Finally, even though my transitional dynamics are associated with both vintages of capital goods, only the new vintage of capital will exist in the new steady state. The length of the transition will, of course, be affected by the size and the distribution of adoption costs.

I calibrate my model to study the dynamic responses of the economy after the arrival of news regarding future productivity. In my model, a period corresponds to one quarter. I set β, the time discount rate, equal to 0.99 to match an average annual interest rate of 4%. I choose ψ to match the empirical observation that the average labor hours is 1/3 in the new steady state, which implies the labor hours being 0.313 in the original steady state. The value of intertemporal elasticity of substitution is set to 1 to imply a log utility function for GHH preference. The Frisch labor supply elasticity, ρ, is set to 10 which is close to the value chosen by Rotember and Woodford (1997).

On the production side, I choose the labor share, ν, to be 0.58 to match the labor income share observed in the postwar US data. The capital share, γ, is set equal to 0.325 so that the annual capital-to-output ratio is 2.315 and the investment-to-output ratio is 0.2315 in steady state.

The values for δ_0 and δ_1 are chosen to imply a steady state capital utilization rate of 1 and a 10% annual depreciation rate, as in the data. In addition, the elasticity of capital utilization, $\delta"(1)/\delta'(1)$, is chosen to be 1 as in Baxter and Farr (2001). Total factor productivity, z, is set to 1 and the capital productivity for new vintage of capital, ε_1, is set to 1.031, together with old vintage, ε_0, being set to 1, to capture a 1% exogenous technological improvement. Finally, I set ξ_L equal to 0 so that new technologies will spread across firms in the long run. Also, I set ξ_U equal to 0.05 to imply a median time to adoption of 7 years later, which lies within the range of diffusion lags found in empirical studies.[8]

4 Results

I use numerical methods to solve for the transitional dynamics of my general equilibrium technology adoption model following news about future technological innovation. As most papers in the news shocks literature focus on economic dynamics over the first twenty quarters following a shock, for comparability, I do the same. In addition, as my model has longer-run implications, I also present a second set of long-run results.

The timing of the news shock I consider is as follows. In period zero, the economy is in the steady state. In period one, news arrives that there will be a 3.1 percent increase in ε_1 in period four (that is a 1% rise in TFP). Figure 1 depicts the short-run response of the economy to this news. It shows that consumption, investment, output, and labor hours increase on impact, in response to positive news about future technology.

Examining this comovement, capital utilization rises instantly with the news shock. This rise in utilization increases labor productivity and total hours worked. The rise in hours is reinforced by the small wealth effect for leisure implied by preferences. At the same time, consumption increases as impending technological improvements raise households' wealth. However, this initial increase in consumption is dampened by my assumption that technology

[8]Mansfield (1989) examines a sample of embodied technologies and finds a median time to adoption of 8.2 years. Comin and Gertler (2004) examine a sample of British data that includes both disembodied and embodied innovations. They find median diffusion lags of 9.8 and 12.5 years, respectively.

is capital-embodied. This links household wealth with the diffusion of the new technology. The more pervasive is the new technology, the greater the effect on aggregate productivity, which is the ultimate determinant of the output and wealth. As technological innovation is capital-embodied, the wealth of the households does not increase until firms actively acquire new capital, and this generates a complementarity between consumption and investment.

Following the news, each firm decides whether to adopt the new capital stock (technology) or continue production using its existing capital. The costs of adoption vary across firms, and those firms facing low fixed costs adopt the new capital immediately, while others delay adoption and continue with the now older vintage of capital. Overall, time-varying adoption costs at the firm level encourage firms to invest in new capital before the ε_1 shock materializes. As a result, my model reverses the problem in the standard DSGE model that investment falls with a positive news shock. Additionally, given differences in their adoption costs, not all firms invest in the frontier technology right away, and both vintages of capital coexist over a transition period.

An interesting feature of my model is that consumption and other series initially rise at impact, then fall until the news shock is realized at date 4. This is driven by a fall in the aggregate capital stock, $\theta k_1 + (1-\theta)qk_0$, over this period. During periods 1 to 3, consumption and investment are higher than in the pre-shock steady state. This increases capital utilization across firms, in particular those operating with capital stock of the older vintage. Higher utilization rates increase depreciation of the capital stock held by old vintage firms, $K_{0t} = (1-\theta_t)k_{0t}$, and thus the aggregate capital, $K_t = q_t K_{0t} + K_{1t}$, where $K_{1t} = \theta_t k_{1t}$. This fall in K_t discourages further increases in employment, and GDP falls relative to its level at the impact date. Nonetheless, over periods 1 to 3, consumption, investment, employment and output all remain above their original pre-shock levels.

Next, I examine differences between firms that adopt the new capital and firms that do not, following the news shock. Over the transition period, the capital utilization rate of firms that have adopted the new vintage of capital is below that of firms that retain the old stock, until period 4 when the ε_1 shock materializes. Higher utilization rates imply faster depreciation and, as the new vintage of capital will become more productive after period 4, it is optimal for firms to wait to use it intensively. Furthermore, even though the total new capital stock held by adopting firms rises monotonically, the capital stock per adopting firm initially rises, then falls, to rise again later on. The temporary fall in firm-level capital is due to an increase in the number of firms adopting. Finally, movements in labor echo the mechanics of firm level capital, thereby equating marginal product of labor across both types of firms. This is seen in Figure 2.

Figure 3 shows the price responses. After the news, wages rise above their original steady

Figure 1: The response to news about future technology improvement.

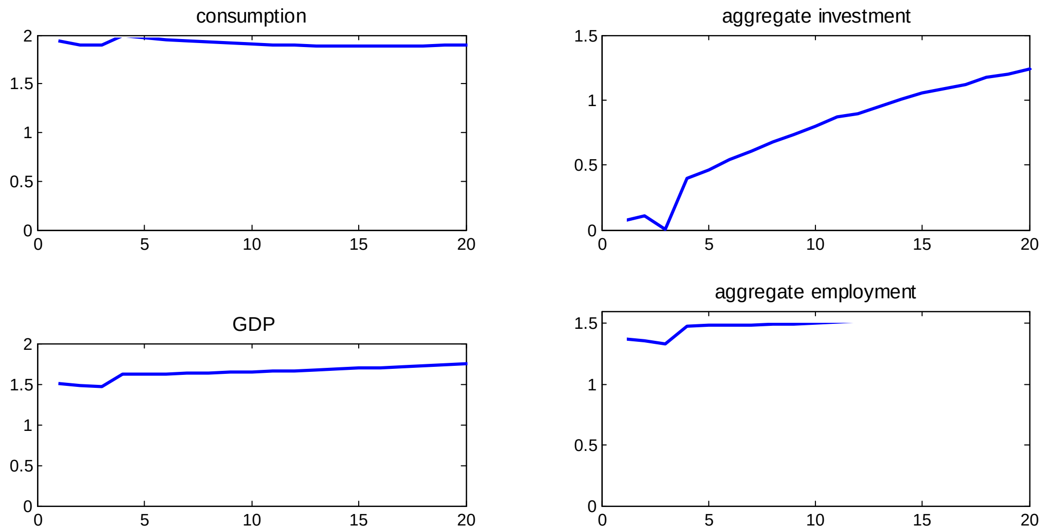


Figure 2: The dynamic adjustment between two types of firms following the arrival of news of future technology improvement.

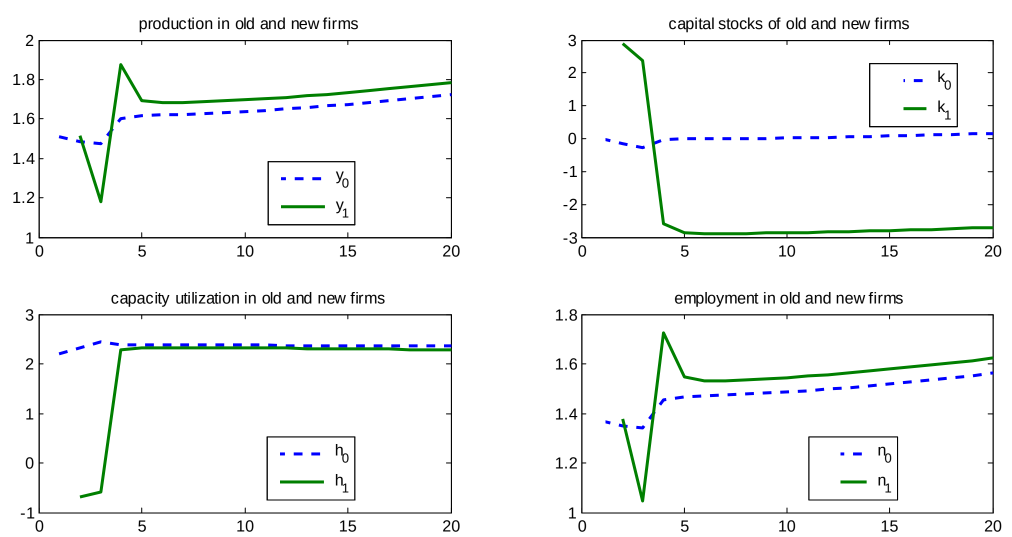
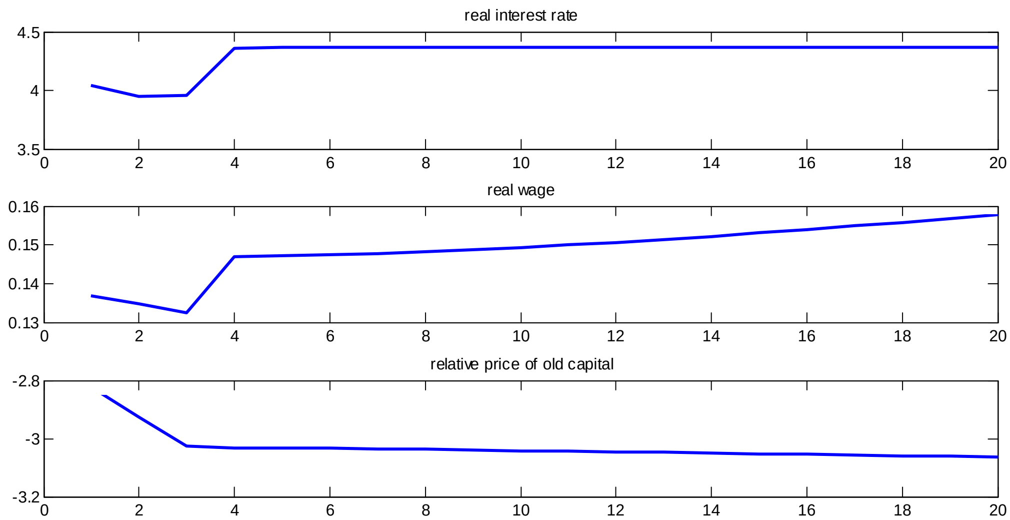


Figure 3: Price adjustment following the arrival of news about future technology improvement.



state level, encouraging households to work harder. The real interest rate falls temporarily, consistent with the dynamics of consumption and labor hours before period 4 when the new technology arrives. Once the technology is available, interest rates rise to mitigate the desire to increase consumption and investment at the same time. Also, the relative price of old capital falls below one since new capital is more valuable than its older counterpart. This is crucial in generating stock price rises on impact which I will discuss later on.

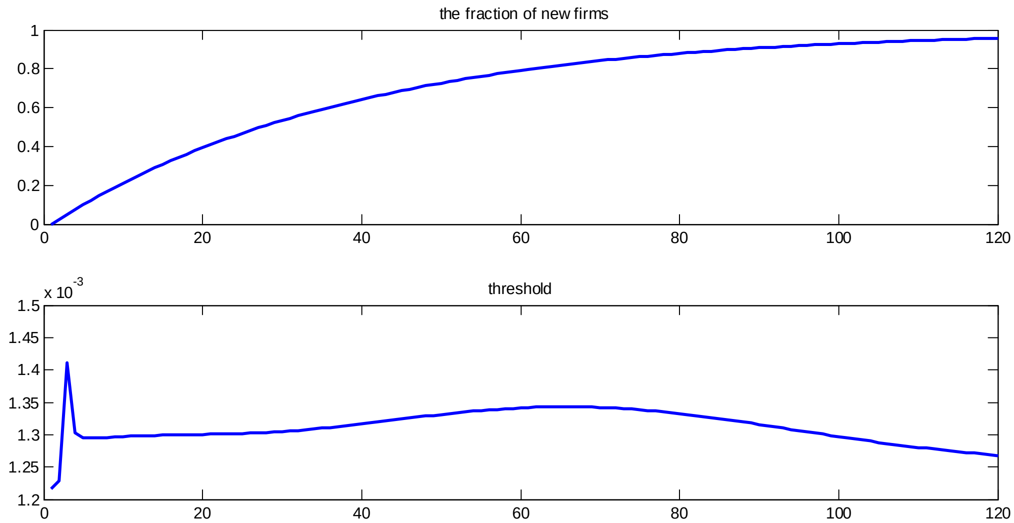
4.1 Long-run results

In this section, I examine the long-run implications of the model. Technological innovation is capital embodied, and there are both direct and indirect costs of technology adoption. The direct cost involves the fixed cost of adoption, while an indirect cost arises through the fall in the relative price of the older capital. These costs slow adoption in the economy, and there is a long period of transition following the arrival of higher productivity capital goods. Given the uniform distribution of technology adoption costs assumed, the fraction of firms that adopt the new technology rises gradually over time; the law of motion of this fraction is

$$\theta' = \frac{\overline{\xi}\left(k_0; z, \theta, s\right) - \xi_L}{\xi_U - \xi_L}(1-\theta) + \theta \tag{28}$$

Figure 4 shows that the median time to adoption is 7 years and it takes about 30 years for

Figure 4: The top panel shows the fraction of firms that have adopted new technologies. The bottom panel displays the path of the threshold adoption costs.



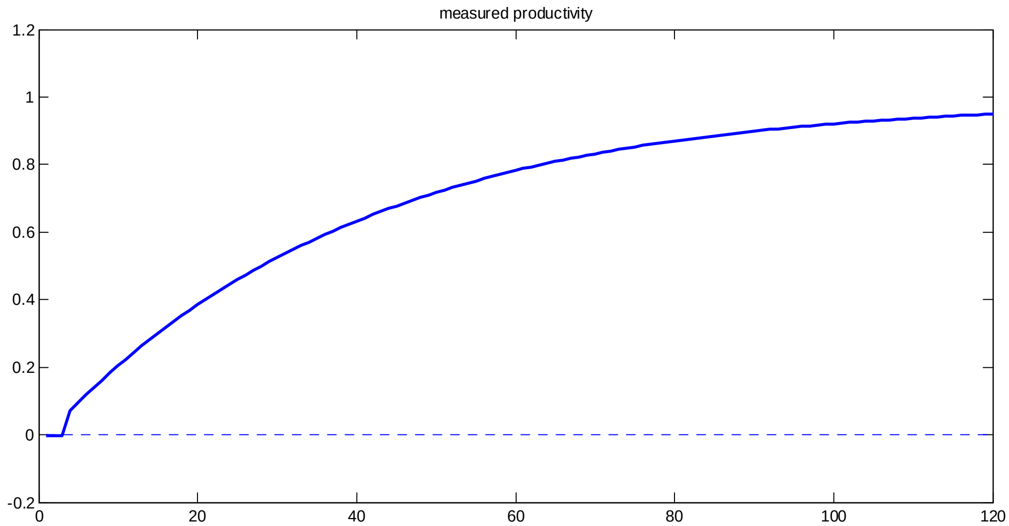
this new technology to diffuse across almost all firms. The rate of adoption varies over time in respect to changes in threshold adoption cost. Recall that the threshold adoption cost is $\overline{\xi}\left(k_0; z, \theta, s\right) = \min\{\xi_U, \max\{\xi_L, \hat{\xi}\left(k_0; z, \theta, s\right)\}\}$, where $\hat{\xi}\left(k_0; z, \theta, s\right) = \frac{E_0^A(k_0;z,\theta,s)-E_0^N(k_0;z,\theta,s)}{p(z,\theta,s)w(z,\theta,s)}$. Changes to the threshold cost arise through the interaction of wages, interest rates, and the future gains from an increase in productivity. Figure 4 displays the evolution of the fraction of firms that have adopted the new technology and the transition path of the threshold cost.

To explore the change in aggregate total factor productivity (TFP) over time, I construct the following measure of TFP, A_t, based on the aggregate production, effective capital, and labor.

$$\log A_t = \log y_t - \gamma \log \sum \theta_{it} h_{it} k_{it} - \nu \log n_t$$

Figure 5 depicts this measure of productivity. Following the arrival of news about future technology improvement, measured productivity rises gradually, rather than jumping to its new long-run level immediately. This result is consistent with historical studies that find that productivity gains following the introduction of new technologies occur slowly over time. For example, productivity did not accelerate immediately following the invention of electricity, but over many years (David, 1990). Similarly, following the IT Revolution, productivity gains did not materialize at the time of new investment in computing equipment; they arrived much later (Brynjolfsson, 1993). Here, the improvement in productivity continues after the event date when new capital goods exhibit higher productivity. This ongoing growth

Figure 5: Measured productivity



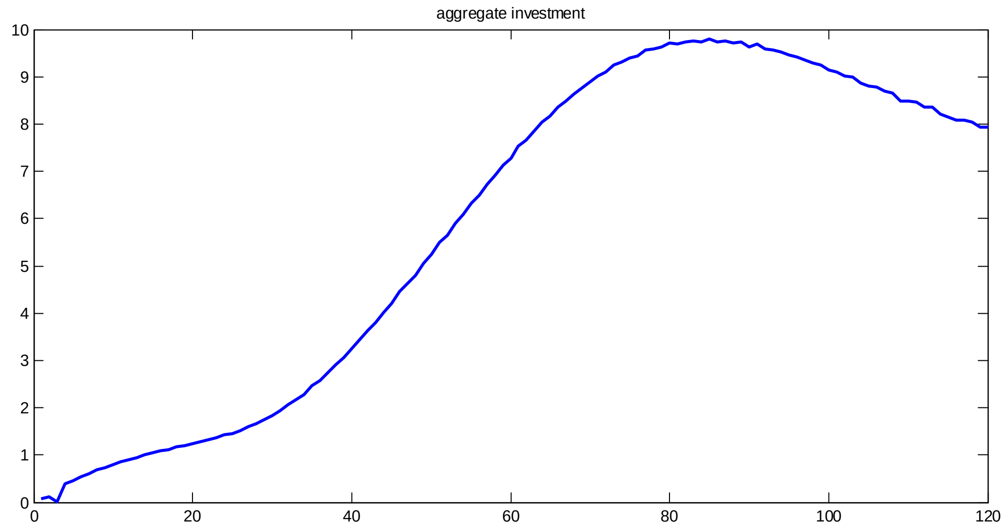
of productivity is due to the slow diffusion of new technologies which spread gradually across firms.

A major unresolved issue in business cycle theory is the construction of an endogenous propagation mechanism capable of capturing the level of persistence observed in the data. Here, though I study only a single discrete change in capital-embodied technology level, aggregate productivity rises gradually toward its new long-run level. Actual TFP depends on both the exogenous change in potential productivity as well as the endogenous adoption decisions of firms. Technology adoption costs help generate a substantial degree of persistence even though the jump in potential productivity is discrete.

During the initial four periods before the arrival of the new technology, measured productivity lies slightly below its original steady state level; it then gradually increases after new capital goods become more productive. This initial fall of TFP is due to an increase in both the capital utilization rate and the labor input over this period. Erik Brynjolfsson (1993) argues that the IT revolution required a large investment in organization costs. However, unlike business fixed investment, this type of spending is counted as a cost rather than final output and hence it depresses the measured productivity. Indeed, in my model, both variable capital utilization and changes in labor drive important wedges between the measured TFP and true TFP. While actual TFP remains constant, we observe an initial fall in measured TFP. This is the result of increases in employment implied by the payment of technology adoption costs.

Investment at the firm level coincides with the technology adoption decision, which itself

Figure 6: Investment exhibits hump-shaped in response to technology improvement.



follows an (S, s) decision rule. This investment behavior is consistent with the finding that large capital adjustments tend to coincide with periods of firm-wide technical change, e.g., Cooper et al., (1993). In addition, investment is hump-shaped at the aggregate level due to the interaction between the extensive margin, the number of firms adopting the new technology, and the intensive margin, the level of investment undertaken by each adopting firm. Following the arrival of news about future technology improvement, the extensive margin dominates initially, while the intensive margin dominates in the long run.

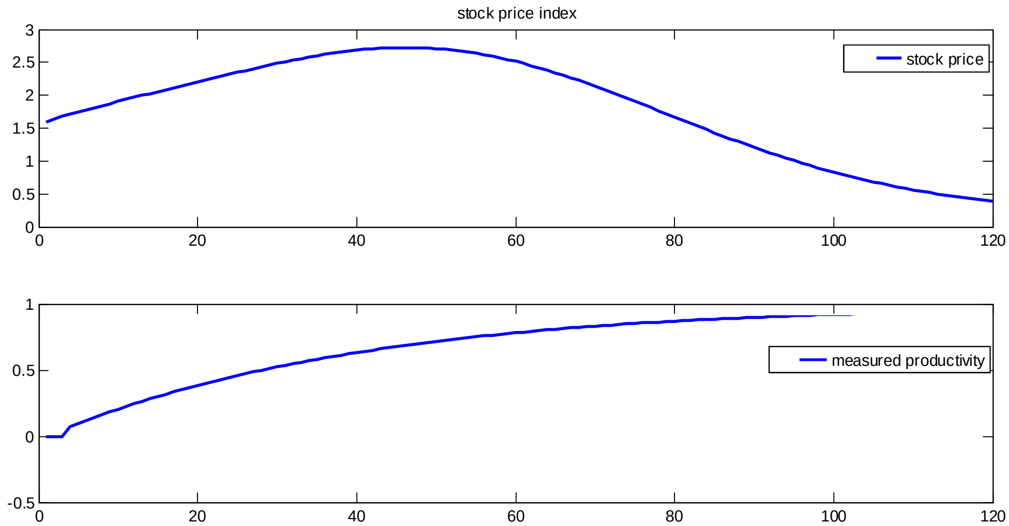
In the model, stock prices reflect households' expectation of firms' future values. I calculate an aggregate stock market index as the weighted average of value per share across firms,

$$SP = \theta \frac{V_1 (k_1; z, \theta, s)}{p(z, \theta, s) k_1} + (1 - \theta) \frac{V_0 (k_0; z, \theta, s)}{q_0 (z, \theta, s) p(z, \theta, s) k_0}.$$

Even though the value of firms using existing technology falls at the date of news shock, the fall in the relative price, and thus the replacement cost, of old vintage capital drives up the stock price. As there is no effect on TFP at this time, the resultant rise in stock price index leads the increase in TFP. This is consistent with the findings of Beaudry and Portier (2006).[9]

[9]BP(2006) actually identify news shocks based on the assumption that stock prices are uncorrelated with current total factor productivity but help predict future productivity.

Figure 7: Stock prices lead measure productivity.



5 Conclusion

Comovement across key macroeconomic aggregates is the central feature of the business cycle. However, in response to news about future increases in total factor productivity, the standard dynamic stochastic general equilibrium model fails to generate comovements in output, consumption, investment, and employment. I extend the model through the introduction of fixed costs of technology adoption and the assumption that technological progress is embodied in new capital goods. This innovation, alongside varying capital utilization and preferences that eliminate wealth effects for leisure, is able to produce business cycle comovement in response to a positive news shock.

There are several new predictions that arise from this analysis. As in the data, the productivity gains from new inventions diffuse slowly through the economy. In the model, this is driven by firm-level differences in the costs of technology adoption. Such costs also make my model consistent with empirical evidence that investment, at the firm-level, is lumpy. Across firms, large investments in capital coincide with the decision to adopt new technologies.

In almost all existing models of news-driven business cycles, firms can costlessly adapt their existing capital for use with new technologies. In contrast, in my model new capital goods must be produced in order to implement new technologies. Another difference between this analysis and related research on news-driven boom-bust cycles involves their application of solution methods that rely on log-linearization. As is well known, the accuracy of such linear methods falls when applied far from the original steady state of a model. My paper instead relies on nonlinear numerical methods involving value function approximation; as these are global methods, they do suffer from accuracy problems when confronted with large shocks. Finally, while I only study a single discrete jump in the level of capital-embodied technology, it is straightforward to extend the model to incorporate ongoing stochastic changes in capital-embodied technology.

While the diffusion of new technology is fairly rapid here, many microeconomic studies find that actual patterns of technology adoption follow an S-shape. Initially, following a new invention, a small fraction of firms adopt the new technology, some time later there is an episode of rapid adoption and the technology becomes widespread. One possible extension of the current model involves the introduction of network effects associated with adopting new technologies. Specifically, the benefit of the new technology for each firm may rise with the number of firms using it. This type of externality may be able to produce the S-shaped patterns of diffusion found in empirical micro studies.

References

[1] Atkeson, Andrew, and Kehoe, Patrick J. 2001, "The transition to a new economy after the Second Industrial Revolution," NBER Working Paper 8676.

[2] Atkeson, Andrew, and Kehoe, Patrick J. 2007, "Modeling the Transition to a New Economy: Lessons from Two Technological Revolutions," *American Economic Review* 97(1),64-88.

[3] Bahk, B.-H and M. Gort (1993), "Decomposing learning by doing in plants," *Journal of Political Economy* 101, 561-583.

[4] Baxter, M. and D. Farr (2001), "Variable factor utilization and international business cycles," NBER Working Paper # 8392.

[5] Beaudry, P. and F. Portier, 2004, "An Exploration into Pigou's Theory of Cycles?" *Journal of Monetary Economics* 51, 1183-1216.

[6] Beaudry, P. and F. Portier, 2006, "News, Stock Prices and Economic Fluctuations," *American Economic Review* 96(4), 1293-1307.

[7] Beaudry, P. and F. Portier, 2007, "When Can Changes in Expectations Cause Business Cycle Fluctuations in Neo-Classical Settings?" *Journal of Economics Theory* 135, 458-477.

[8] Barsky, R. and E. Sims (2009) "Information, Animal Spirits, and the Meaning of Innovations in Consumer Confidence," NBER Working Paper 15049.

[9] Boddy, Raford and Gort, Michael, 1974, "Obsolescence, Embodiment, and the Explanation of Productivity Change," *Southern Economic Journal*, 40(4), 553-562.

[10] Campbell, J. R., 1998, "Entry, exit, technology, and business cycles," *Review of Economic Dynamics*, 1, 371-408.

[11] Cooley, Thomas F., Jeremy Greenwood, and Mehmet Yorukoglu, 1997, "The Replacement Problem," *Journal of Monetary Economics*, 40(3), 457-99.

[12] Cooper, Russell, Haltiwanger, John and Power, Laura, 1999, "Machine Replacement and the Business Cycle: Lumps and Bumps," *American Economic Review*, 89(4), 921-946.

[13] Christiano, Lawrence J., Eichenbaum Martin, and Evans Charles L., 2005, "Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy," *Journal of Political Economy*, 113, 1-45.

[14] Christiano, L., C. Ilut, R. Motto, and M. Rostagno, 2007, "Monetary Policy and a Stock Market Boom-Bust Cycle," working paper, Northwestern University.

[15] Comin, Diego, Gertler, Mark and Santacreu, Ana Maria, 2008, "News, technology adoption and economic fluctuations" working paper.

[16] Cochrane, John H, 1994, "Shocks," *Carnegie–Rochester Conference Series on Public Policy*, 41, pp. 295–364.

[17] Cooley, T. F., Greenwood, J., and Yorukoglu, M., 1997, "The replacement problem," *Journal of Monetary Economics*, 457-499.

[18] David, Paul A., 1990, "The Dynamo and the Computer: An Historical Perspective on the Modern Productivity Paradox," *American Economic Review*, 80(2), 355-61.

[19] David, Paul A., 1991, "Computer and Dynamo: The Modern Productivity Paradox in a Not-Too Distant Mirror," In Technology and Productivity: The Challenge for Economic Policy, 315-45. Paris: Organisation for Economic Co-operation and Development.

[20] David, Paul A., and Gavin Wright, 1999, "General Purpose Technologies and Surges in Productivity: Historical Reflections on the Future of the ICT Revolution," Standford University Department of Economics Working Paper 99-026.

[21] Devine, Warren D., Jr. 1983, "From Shafts to Wires: Historical Perspective on Electrification," *Journal of Economic History*, 43(2):347-72.

[22] Doms, M., Dunne, T., 1998, "Capital adjustment patterns in manufacturing plants," *Review of Economic Dynamics*, 1, 409-29.

[23] Eric Sims, 2008, "Expectations Driven Business Cycles: An Empirical Evaluation," working paper, University of Michigan.

[24] Erik Brynjolfsson, 1993, "The Productivity Paradox of Information Technology: Review and Assessment," *Communications of the ACM*, 36(12), 66-77.

[25] Greenwood, Jeremy, Hercowitz, Zvi and Huffman, Gregory W, 1988, "Investment, Capacity Utilization, and the Real Business Cycle," *American Economic Review*, 78(3), 402-17.

[26] Greenwood, Jeremy, Hercowitz, Zvi and Krusell, P., 1996, "Long-run implications of investment-specific technological change," *American Economic Review*, 87, 342-362.

[27] Jaimovich, N. and S. Rebelo, 2008, "Can News about the Future Drive the Business Cycle?" working paper, Northwestern University.

[28] Jovanovic, Boyan, and Saul Lach, 1989, "Entry, Exit and Diffusion with Learning by Doing," *American Economic Review*, 79(4):690-99.

[29] Jovanovic, Boyan, and Yaw Nyarko, 1995, "A Bayesian Learning Model Fitted to a Variety of Empirical Learning Curves," *Brookings Papers on Economic Activity, Microeconomics*: 247-99.

[30] Jovanovic, Boyan, and Yaw Nyarko, 1996, "Learning by Doing and the choice of technology," *Econometrica*, 64, 1299-1310.

[31] Jovanovic, Boyan, and Peter L. Rousseau, 2005, "General Purpose Technologies," National Bureau of Economic Research Working Paper 11093.

[32] Khan, Aubhik and Ravikumar, B., 2002, "Costly Technology Adoption and Capital Accumulation," *Review of Economic Dynamics*, 5(2), 489-502.

[33] Khan, Aubhik and Thomas, Julia K., 2003, "Nonconvex factor adjustments in equilibrium business cycle models: do nonlinearities matter?," *Journal of Monetary Economics*, 50(2), pages 331-360.

[34] Rotemberg, Julio, and Michael Woodford, 1997, "An Optimization-Based Econometric Framework for the Evaluation of Monetary Policy," *NBER Macroeconomics Annual*, 297-346.

[35] Schmitt-Grohe, Stephanie and Uribe, Martin, 2008, "What's News In Business Cycles," NBER Working Papers 14215.

[36] Schurr, Sam H., Calvin C. Burwell, Warren D. Devine, Jr., and Sidney Sonenblum. 1990. Electricity in the American Economy: Agent of Technological Progress. Westport: Greenwood Press.

[37] Schurr, Sam H., Bruce C. Netschert, Vera Eliasberg, Joseph Lerner, and Hans H. Landsberg. 1960. Energy in the American Economy, 1850-1975: An Economy Study of Its History and Prospects. Baltimore: John Hopkins University Press.