Monetary Policy and Shifts in Long Run Productivity Growth*

Rochelle M. Edge,[†] Thomas Laubach,[‡] and John C. Williams[§]

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[†]Federal Reserve Board, rochelle.m.edge@frb.gov.

[‡]Federal Reserve Board and OECD, thomas.laubach@oecd.org. (*Corresponding author.*)

[§]Federal Reserve Bank of San Francisco, john.c.williams@sf.frb.org.

Abstract

The productivity slowdown in the 1970s and the speedup in the late 1990s presented difficult challenges to monetary policymakers. The productivity slowdown has been blamed for the 1970s stagflation episode—contemporaneous stagnant growth, high unemployment, and high inflation—while the productivity acceleration has similarly been credited with powering the disinflationary boom of the late 1990s. In both cases, monetary policy is believed to have been important in determining the economy's response to the shift in long-run growth. Although there has been a great deal of study documenting these events, there has been surprisingly little formal analysis of the appropriate monetary policy response to shifts in the growth rate of productivity. Intuitively, it is clear that policy should somehow "accommodate" supply shocks such as these, but the question is, what does that imply for the setting of interest rates? In particular, should real interest rates—which will eventually move in the same direction as the change in the rate of productivity growth—rise or fall in response to technology shocks and how much does monetary policy matter for the evolution of real and nominal variables? A further challenge for monetary policy makers arises from the difficulty in identifying in real time shifts in the growth rate of productivity.

In this paper, we examine the effects of (and appropriate policy response to) shifts in the growth rate of long-run multifactor productivity (MFP), where in doing so we recognize the important practical consideration that the underlying growth rate in MFP growth is unobservable in real time and must therefore be inferred from available data. We conduct our monetary policy analysis using the two-sector DGE model developed and estimated in Edge, Laubach, and Williams (2003), and modified here to allow for persistent changes in trend productivity growth. The model incorporates habit formation in consumption, investment adjustment costs, variable capacity utilization, sticky wages and prices, and imperfect information regarding the permanence of shocks to productivity growth. We find that shifts in the long-run productivity growth rate have sizable and highly persistent effects on the real economy and inflation. In addition, these responses, particularly those of employment and inflation, are sensitive to the specification of monetary policy. This latter result contrasts with that found using stylized New Keynesian models, in which the response to growth rate shocks is relatively insensitive to the particular specification of policy.
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1 Introduction

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This paper's agenda ties in with recent work by Galí, López-Salido, and Vallés (forthcoming), which considers the optimal monetary policy response to transitory shifts in the growth rate of MFP, and Galí (2000), which extends the analysis to include permanent shifts in the growth rate of trend MFP.[2] Galí *et al.* and Galí assume that sticky prices

[1]The specification of this model is similar to those of Christiano, Eichenbaum and Evans (2001) and Smets and Wouters (2002), so our results should apply to those models as well.

[2]Svensson and Woodford (2003)—as a specific example to illustrate their more general solution method for determining the optimal weights for policymakers to place on different forward-looking and partially-informative macroeconomic indicators—also consider how monetary policy should respond to shifts in MFP

are the only source of nominal rigidity; consequently, their prescribed policy in response to MFP growth rate movements—which exactly replicates the flex-price model's response—eliminates simultaneously both the output gap and inflation rate variances (upon which utility based welfare depends).

In this paper, we consider the more general case of sticky wages *and* prices, as well a number of additional empirically-supported features in the model, including habit-persistence in consumption, and adjustment-costs in investment spending, and find that these modifications to the model have profound effects on the effects of monetary policy on the model economy and on the characteristics of optimal policy responses.[3]

The outline of the paper is as follows. Section 2 presents the technologies and preferences for the model used in our monetary policy analysis; section 3 outlines the decentralization of the model, including the signal extraction problem faced by agents in inferring changes in long-run MFP growth from observed movements in MFP; and, section 4 describes the estimation and calibration of the model's parameters. We then turn to the policy analysis component of the paper and examine in section 5 the responses to shifts in long-run growth under alternative monetary policies. Section 6 concludes.

2 Technology and Preferences

In this section, we describe the technology and preferences describing our model, which was developed and estimated in Edge, Laubach, and Williams (2003). This model shares many features with those developed by Fuhrer (1997b), Christiano, Eichenbaum, and Evans (2003), Smets and Wouters (2002), and Altig, Christiano, Eichenbaum, and Linde (2002). Importantly, the dynamics of nominal and real variables are determined by first-order conditions of optimizing agents. In order for the model to fit the data reasonably well, we allow for various frictions such as habit formation and investment adjustment costs that interfere

growth.

[3]The inclusion of many of these additional features to the model have been already studied in the context of optimal monetary policy more broadly the consideration of the implications of endogenous capital accumulation for optimal policy have remained largely untouched. See Erceg, Henderson, and Levin, 2000, and Amato and Laubach, 2003, on the the implications of both sticky-prices and sticky-wages and Amato and Laubach, 2004, on the implications of habit-persistence.

with instantaneous full adjustment in response to shocks.[4] As in Altig *et al.* (2002), ours is a two-sector model in which the level and growth rates of technology are allowed to differ across the consumption and investment goods sectors. In the next section we turn to the decentralization of this economy and derive the conditions describing the decentralized equilibrium.

2.1 The Production Technology

Two distinct final goods are produced: consumption goods (denoted $Y_{c,t}$) and investment goods (denoted $Y_{i,t}$). Given the current levels of technology in each final goods sector denoted by $A_{s,t}$ for sector s, consumption and investment goods are produced by aggregating—according to a Dixit-Stiglitz technology—an infinite number of differentiated intermediate material goods. Specifically, final goods production in sector s in period t is represented by the function

$$Y_{s,t} = A_{s,t}^{1-\alpha} \left(\int_0^1 Y_{m,s,t}(x)^{\frac{\theta-1}{\theta}} dx \right)^{\frac{\theta}{\theta-1}}, \ s = c, i, \tag{1}$$

where the variable $Y_{m,s,t}(x)$ denotes the quantity of the intermediate materials good indexed by type $x \in [0, 1]$ used to produce final output in sector s and θ is the elasticity of substitution between the differentiated materials inputs used in the production, assumed to be the same in both sectors.

The differentiated intermediate materials goods used as inputs in equation (1) are themselves produced by combining each variety of our economy's differentiated labor inputs $\{L_t(x)\}, x \in [0, 1]$ with physical capital K_t. Capital can be utilized at varying intensities, denoted by $U_t \geq 0$. A Dixit-Stiglitz aggregator characterizes the way in which differentiated labor inputs are used together in the production of the economy's materials goods, while a Cobb-Douglas production function then characterizes how the composite bundle of labor, denoted L_t, is combined with utilized capital to produce, given the current level of technology $A_{m,t}$, output of intermediate materials goods. The production of materials good z, for $z \in [0, 1]$, is determined by:

$$Y_{m,t}(z) = (K_t(z)U_t(z))^{\alpha} (A_{m,t}L_t(z))^{1-\alpha} - K_t(z)\Psi(U_t(z))(A_{i,t})^{-(1-\alpha)} \tag{2}$$

$$\text{where } L_t(z) = \left(\int_0^1 L_t(x,z)^{\frac{\omega-1}{\omega}} dx \right)^{\frac{\omega}{\omega-1}}, \tag{3}$$

[4] Estrella and Fuhrer (2002) document the shortcomings of optimization-based models that do not incorporate such sources inertia.

where the function $\Psi(U_t) = \frac{\mu}{\psi+1}\left(U_t^{\psi+1} - 1\right)$ has the properties that $\Psi(1) = 0$, $\Psi'(1) = \mu(1)^\psi = \mu \geq 0$, and $\Psi''(1) = \mu\psi(1)^{\psi-1} = \mu\psi \geq 0$. The parameter α denotes the elasticity of output with respect to capital, while ω denotes the elasticity of substitution between the differentiated labor inputs.

2.2 The Capital Evolution Technology

The law of motion for the economy's beginning of period $t+1$ capital stock K_{t+1} is given by:

$$K_{t+1} = (1-\delta)K_t + I_t \exp\left[-\frac{\chi_i}{2}\left(\frac{I_t}{I_{t-1}} - \Gamma_i\right)^2\right], \tag{4}$$

where I_t is gross investment, δ is the depreciation rate, and Γ_i is the steady-state growth rate of investment. The final term multiplying I_t measures the fraction of investment that contributes to the capital stock after adjustment costs. The fraction of investment lost to adjustment costs is zero when investment growth, I_t/I_{t-1}, equals the trend rate of growth of technology in the investment goods sector, but rises to above zero, at an increasing rate, as investment growth moves further away from its trend. The parameter $\chi_i \geq 0$ governs how quickly adjustment costs increase as investment growth moves away from Γ_i. The economy's resource constraint implies that $I_t \leq Y_{i,t}$.

2.3 Preferences

Households derive utility from their purchases of the consumption good C_t and from their use of leisure time, equal to what remains of their time endowment $\bar{L}$ after $0 \leq L_t(i) \leq \bar{L}$ hours of labor are supplied to market activities. The preferences of household $i \in [0,1]$ over consumption and leisure are nonseparable, with household i's consumption habit stock (assumed to equal a fraction $\eta \in [0,1]$ of its consumption last period) influencing the utility it derives from current consumption. Note that we assume that utility is nonseperable between consumption and leisure, consistent with evidence of Basu and Kimball (2002). Specifically, preferences of household i are given by

$$E_0 \frac{1}{1-\sigma} \sum_{t=0}^{\infty} \beta^t \left[(C_t(i) - \eta C_{t-1}(i))(\bar{L} - L_t(i))^\zeta\right]^{1-\sigma}, \tag{5}$$

where β is the household's discount factor, and ζ is a measure of the utility of leisure. The economy's resource constraint implies that $\int_0^1 C_t(x)dx \leq Y_{c,t}$.

2.4 Productivity Growth

The log-level of technology in each of the three sectors ($s = c, i, m$) is modeled as a random walk with stochastic drift. Specifically,

$$\ln A_{s,t} = \ln \Gamma_{a,s,t} + \ln A_{s,t-1} + \epsilon_{s,t} \qquad \epsilon_{s,t} \sim N(0, \sigma^2_{\epsilon,s}), \tag{6}$$

$$\ln \Gamma_{a,s,t} = (1-\rho) \ln \bar{\Gamma}_{a,s} + \rho \ln \Gamma_{a,s,t-1} + \nu_{s,t} \qquad \nu_{s,t} \sim N(0, \sigma^2_{\nu,s}), \tag{7}$$

where $\epsilon_{s,t}$ and $\nu_{s,t}$ are assumed to be serially uncorrelated with Gaussian distribution and zero contemporaneous correlation. The disturbance $\epsilon_{s,t}$ corresponds to a permanent shock to the *level* of productivity (and a transitory shock to its *growth rate*), while $\nu_{s,t}$ is a shock to the trend *growth rate* of productivity. The process specified above is similar to that used in Edge, Laubach, and Williams (2004), the only difference being that in equation (7) the growth process $\ln \Gamma_{a,s,t}$ follows an auto-regressive process, whereas in Edge *et al.* the growth process $\ln \Gamma_{a,s,t}$ followed a random walk.

The paper considers two different informational structures regarding the economy's technology evolution process. We first assume that agents can observe all of the components of the economy's productivity process, that is, the variables, $\{A_{s,t}, \Gamma_{a,s,t}\}_{t=0}^{\infty}$, and the shocks $\{\epsilon_{s,t}, \nu_{s,t}\}_{t=0}^{\infty}$. Edge, Laubach, and Williams (2004), however, find that this is not a very appealing set-up since under this informational assumption the model's predictions of how the economy responds to persistent shifts in the growth rate of technology conflict sharply with the empirically observed responses of macroeconomic variables following episodes in which productivity growth has increased or decreased.[5] Consequently, we also consider the possibility in which only $\{A_{s,t}\}_{t=0}^{\infty}$ can be observed so that agents must infer (given their knowledge of the underlying technology process, summarized by equations 6 and 7 and the parameters $\sigma^2_{\epsilon,s}$, $\sigma^2_{\mu,s}$, and ρ), the transitory $\{\epsilon_{s,t}\}_{t=0}^{\infty}$ and permanent $\{\Gamma_{a,s,t}, \nu_{s,t}\}_{t=0}^{\infty}$ components of productivity growth. This informational structure, which requires agents to solve a signal extraction problem in addition to the usual profit- or utility-maximization problems that they otherwise solve, implies responses to persistent MFP growth rate shocks that conform more closely with those observed empirically.[6]

[5] If immediately recognized, an increase in the trend growth rate of productivity causes long-term interest rates to rise and generates a sharp decline in employment and investment.

[6] Allowing for the gradual recognition of shifts in the trend growth rate of productivity can, following a sustained rise in the rate of productivity growth, generate a more gradual increase in long-term interest rates and consequently prolonged positive responses for hours and investment.

3 The Decentralized Economy

We now discuss the agents of our economy and their respective optimization problems. We assume the following decentralization. There is one representative, perfectly competitive firm in each of the two final-goods producing sectors, which purchases intermediate inputs from the continuum of materials goods producers. The materials goods producers, in turn, rent capital from a perfectly competitive representative capitalist, and differentiated types of labor from households. The capitalist purchases the investment good from the investment-goods producing firm, and households purchase the consumption good from the consumption-goods producing firm. Because both materials goods producers and households are monopolistic competitors, they also set prices at which they supply their respective products or labor services.

An additional problem for agents arises when we assume the informational structure in which only the level of productivity, $A_{s,t}$ can be observed, while its components $\Gamma_{a,s,t}$, $\epsilon_{s,t}$, and $\nu_{s,t}$ must be inferred. The resulting additional signal extraction problem is outlined in the following section.

3.1 Agents' Signal Extraction of Technology Shocks

In the case in which only the level of technology $A_{s,t}$ can be observed, we assume that final and intermediate goods producers know the structure of the process underlying MFP growth, that is the equations (6) and (7) and the parameters $\sigma^2_{\epsilon,s}$, $\sigma^2_{\nu,s}$, and ρ. Consequently, agents are able to use the Kalman filter to estimate the separate components of technology, that is $\Gamma_{a,s,t}$, $\epsilon_{s,t}$, and $\nu_{s,t}$.[7]

A key advantage of the Kalman filter is that under a particular set of assumptions regarding the data generating processes for productivity growth, it reduces to a simple linear updating formula for estimating the trend rate of productivity growth. Given a new observation of z_t, the prior estimate of the trend growth rate $\hat{g}_{z,t-1}$ is updated by applying the steady-state Kalman filter:

$$\ln \hat{\Gamma}_{a,s,t} = \ln \hat{\Gamma}_{a,s,t-1} + \lambda(\ln A_{s,t} - \ln A_{s,t-1} - \ln \hat{\Gamma}_{a,s,t-1}), \tag{8}$$

[7] See Stock and Watson 1998, Brainard and Perry 2000, Roberts 2001, Laubach and Williams 2003 for examples of uses the Kalman filter in estimating the trend growth rate of productivity or output.

where λ, the steady-state gain, is given by

$$\lambda = \frac{1}{2}\left\{\phi - (1-\rho^2) + \sqrt{\phi - (1-\rho^2) + 4\phi}\right\}, \tag{9}$$

where $\phi = \sigma^2_{\nu,s}/\sigma^2_{\epsilon,s}$, signal-to-noise ratio, is strictly positive. By implication

$$\hat{\epsilon}_{s,t} = \ln A_{s,t} - \ln A_{s,t-1} - \ln \hat{\Gamma}_{a,s,t} \text{ and } \hat{\nu}_{s,t} = \ln \hat{\Gamma}_{a,s,t} - \rho \ln \hat{\Gamma}_{a,s,t-1} + (1-\rho)\ln \bar{\Gamma}_{a,s}.$$

This filter is optimal under the assumptions of the model (see Harvey 1989 for a full treatment) and, as shown in Edge, Laubach, and Williams (2004), the implied linear updating rule can be parameterized so as to approximate well the real-time estimates of long-run labor productivity growth.

3.2 Final Goods Producers

The competitive firm in the consumption good sector owns the production technology described in equation (1) for $s = c$, while the competitive firm in the capital goods sector owns the same technology for $s = i$. Each final-good producing firm, taking as given the prices set by each intermediate-good producer for their differentiated output, that is $\{P_{m,t}(j)\}_{j=0}^{1}$, chooses intermediate inputs $\{Y_{m,s,t}(j)\}_{j=0}^{1}$ so as to minimize the cost of producing its final output $Y_{s,t}$, subject its production technology, given by equation (1). Specifically, the competitive firm in each sector solves

$$\min_{\{Y_{m,s,t}(j)\}_{j=0}^{1}} \int_0^1 P_t(x) Y_{m,s,t}(x)dx \text{ s.t. } Y_{s,t} \leq A_{s,t}^{1-\alpha}\left(\int_0^1 Y_{m,s,t}(x)^{\frac{\theta-1}{\theta}}dx\right)^{\frac{\theta}{\theta-1}},\ s = c, i. \tag{10}$$

The cost-minimization problems solved by firms in the economy's consumption and capital goods producing sectors imply economy-wide demand functions for each intermediate good that are given by

$$Y_{m,t}(j) = \left(\frac{P_{m,t}(j)}{P_{m,t}}\right)^{-\theta} \sum_{s=c,i} \frac{Y_{s,t}}{A_{s,t}^{1-\alpha}}. \tag{11}$$

The variable $P_{m,t}$ denotes the aggregate price level in the intermediate goods sector and is defined by $P_{m,t} = (\int_0^1 (P_{m,t}(x))^{1-\theta}dx)^{\frac{1}{1-\theta}}$. The cost-minimization problems solved in each final-good producing sector imply that the competitive price for consumption and investment goods, respectively, are given by $P_{c,t} = P_{m,t}A_{c,t}^{-(1-\alpha)}$ and $P_{i,t} = P_{m,t}A_{i,t}^{-(1-\alpha)}$.

3.3 Intermediate Goods Producers

Each intermediate (or materials) good producing firm $j \in [0,1]$ owns the production technology described in equations (2) and (3). In considering firm j's problem—of choosing the quantities of differentiated labor services $\{L_t(i,j)\}_{i=0}^1$, capital $K_t(j)$, and the degree of utilization $U_t(j)$ that it will use in production—it is convenient to split the decision into two separate stages. In the first step of the problem firm j, taking as given the wages $\{W_t(i)\}_{i=0}^1$ set by each household for its variety of labor, chooses $\{L_t(i,j)\}_{i=0}^1$ to minimize the cost of attaining the aggregate labor bundle $L_t(j)$ that it will ultimately need for production. Specifically, the materials firm j solves:

$$\min_{\{L_t(i,j)\}_{i=0}^1} \int_0^1 W_t(x) L_t(x,j) dx \quad \text{s.t.} \quad L_t(j) \leq \left(\int_0^1 L_t(x,j)^{\frac{\omega-1}{\omega}} dx \right)^{\frac{\omega}{\omega-1}} \tag{12}$$

The cost-minimization problem undertaken by each materials producing firm implies that the economy-wide demand for type i labor is

$$L_t(i) = \int_0^1 L_t(i,x) dx = \left(\frac{W_t(i)}{W_t} \right)^{-\omega} \int_0^1 L_t(x) dx \tag{13}$$

where W_t denotes the aggregate wage, defined by $W_t = (\int_0^1 (W_t(x))^{1-\omega} dx)^{\frac{1}{1-\omega}}$. In the second step of the problem firm j, taking as given the aggregate wage W_t and the rental rate on capital $R_{k,t}$, chooses aggregate labor $L_t(j)$, capital $K_t(j)$, and utilization $U_t(j)$ to minimize the costs of attaining its desired level of output $Y_{m,t}(j)$. Specifically, the firm solves

$$\begin{aligned} \min_{K_t(j), L_t(j), U_t(j)} \quad & R_{k,t} K_t(j) + W_t L_t(j) \\ \text{s.t.} \quad & Y_{m,t}(j) \leq (K_t(j) U_t(j))^{\alpha} (A_{m,t} L_t(j))^{1-\alpha} - K_t(j) \Psi(U_t(j)) (A_{i,t})^{-(1-\alpha)}. \end{aligned} \tag{14}$$

Since each firm produces its own differentiated variety of materials output $Y_{m,t}(j)$, it is able to set its price $P_{m,t}(j)$, which it does taking into account the demand schedule for its output that it faces from the consumption and capital goods sectors (equation 11). Intermediate materials goods-producing firms are assumed to face non-negative adjustment costs in altering both the level and the rate of change in their prices. For this purpose, we apply the generalized adjustment cost model due to Tinsley (1993) and discussed in Kozicki and Tinsley (1999). We prefer this approach over that of common alternatives because the latter imply heterogeneity among agents. Partly for this reason, models utilizing staggered price and wage setting typically assume that utility is separable between consumption and leisure, in which case perfect insurance among households against labor income risk eliminates heterogeneity of their spending decisions. By contrast, if wages are staggered and household utility is nonseparable, differences across households in labor supply (which will result due to differences in wages set) lead to differences across household in the marginal utility of consumption (and hence consumption), even if perfect insurance is able to equalize wealth across households. The quadratic adjustment cost model allows us to avoid heterogeneity across agents. In any case, the resulting price and wage inflation equations are very similar to those derived from Calvo-based setups with inertia as in Christiano, Eichenbaum, and Evans (2003) and Smets and Wouters (2002).

The price adjustment costs (denote by $\chi_{p,1}$ and $\chi_{p,2}$, respectively) appear as an expense against firms' profits and are thus factored into their profit-maximization problem. The intermediate-good producing firm j, taking as given the marginal cost $MC_{m,t}(j)$ for producing $Y_{m,t}(j)$, the aggregate material price level $P_{m,t}$, and aggregate materials output $Y_{m,t}$, chooses its price $P_{m,t}(j)$ to maximize the present discounted value of its profits subject to the demand curve it faces for its differentiated output (equation 11). The materials producer's profit-maximization problem is given by

$$\max_{\{P_{m,t}(j)\}_{t=0}^{\infty}} E_0 \sum_{t=0}^{\infty} \beta^t \frac{\Lambda_{c,t}}{P_{c,t}} \Bigg\{ (1+\varsigma_\theta) P_{m,t}(j) Y_{m,t}(j) - MC_{m,t}(j) Y_{m,t}(j) - \left[\frac{\chi_{p,1}}{2} \left(\Pi_{m,t}(j) - \bar{\Pi}_m \right)^2 + \frac{\chi_{p,2}}{2} \left(\frac{\Pi_{m,t}(j)}{\Pi_{m,t-1}(j)} - 1 \right)^2 \right] P_{m,t} Y_{m,t} \Bigg\}$$

$$\text{s.t. } Y_{m,t}(j) = \left(\frac{P_{m,t}(j)}{P_{m,t}} \right)^{-\theta} \left(\frac{Y_{c,t}}{A_{c,t}^{1-\alpha}} + \frac{Y_{i,t}}{A_{i,t}^{1-\alpha}} \right), \tag{15}$$

where the discount factor that is relevant when comparing nominal revenues and costs in period t with those in period $t+j$ is $E_t \beta^j \frac{\Lambda_{c,t+j}/P_{c,t+j}}{\Lambda_{c,t}/P_{c,t}}$, where $\Lambda_{c,t}$ is the household's marginal utility of consumption in period t. The parameter $\bar{\Pi}_m$ is the steady-state rate of aggregate materials price inflation and $\varsigma_\theta = (\theta-1)^{-1}$ is a subsidy to production that is set to ensure that the economy's level of steady-state output is Pareto optimal.

3.4 Capital Owners

The capitalist possesses the technology described in equation (4) for transforming capital goods, purchased from capital goods producers, into capital that can be rented and used productively by materials firms. The competitive capitalist, taking as given the rental rate on capital $R_{k,t}$, the price of investment goods $P_{i,t}$, and the stochastic discount factor chooses investment to maximize the present discounted value of profits subject to the law of motion governing the evolution of capital (equation 4).[8] Specifically, the capitalist solves:

$$\max_{\{I_t,K_{t+1}\}_{t=0}^{\infty}} E_0\sum_{t=0}^{\infty}\beta^t\frac{\Lambda_{c,t}}{P_{c,t}}[R_{k,t}K_t-P_{i,t}I_t] \text{ s.t. } K_{t+1}\leq(1-\delta)K_t+I_t\exp\left[-\frac{\chi_i}{2}\left(\frac{I_t}{I_{t-1}}-\Gamma_k\right)^2\right]. \quad (16)$$

3.5 Households

The representative household's utility, which is defined over consumption and leisure, is described by equation (5). Since each household supplies its own differentiated variety of labor $L_t(i)$, it is able to set its wage $W_t(i)$ subject to the labor demand schedule that it faces from the materials producing sector (equation 13). Analogous to materials producers, the household faces non-negative adjustment costs (denoted by $\chi_{w,1}$ and $\chi_{w,2}$) in terms of altering both the level and growth rate of its nominal wage. These adjustment costs appear as an expense against income in the household's budget constraint and are thus factored into the household's utility-maximization problem. The household's budget constraint with costly wage adjustment is is given by

$$E_t\left[\beta\frac{\Lambda_{c,t+1}/P_{c,t+1}}{\Lambda_{c,t}/P_{c,t}}B_{t+1}(i)\right]=B_t(i)+(1+\varsigma_\omega)W_t(i)L_t(i)+\mathit{Profits}_t(i)-P_{c,t}C_t(i)$$
$$-\left[\frac{\chi_{w,1}}{2}\left(\Pi_{w,t}(i)-\bar{\Pi}_w\right)^2-\frac{\chi_{w,2}}{2}\left(\frac{\Pi_{w,t}(i)}{\Pi_{w,t-1}(i)}-1\right)^2\right]W_tL_t, \quad (17)$$

where the variable $B_t(i)$ is the state-contingent value, in terms of the numeraire, of household i's asset holdings at the beginning of period t. We assume that there exists a risk-free one-period bond, which pays one unit of the numeraire in each state, and denote its yield—that is, the gross nominal interest rate between periods t and $t+1$—by $R_t\equiv\left(E_t\beta\frac{\Lambda_{c,t+1}/P_{c,t+1}}{\Lambda_{c,t}/P_{c,t}}\right)^{-1}$. Profits are those repatriated from capitalist and materials producing firms who, as already noted, are ultimately owned by households. The parameter $\bar{\Pi}_w$ is the steady-state rate of aggregate nominal wage inflation and $\varsigma_\omega=(\omega-1)^{-1}$ is a subsidy to production that is set to ensure that the household's level of steady-state labor supply (and hence the economy's level of steady-state output) is Pareto optimal.

The household takes as given the expected path of the gross nominal interest rate R_t, the consumption good price level $P_{c,t}$, the aggregate wage rate W_t, profits income, and the

[8] The economy's capital stock is also ultimately owned by the households, so that the relevant discount factor in comparing nominal earnings and expenditures in period t with those in period $t+j$ is $\beta^j\frac{\Lambda_{c,t+j}/P_{c,t+j}}{\Lambda_{c,t}/P_{c,t}}$.

initial bond stock $B_{i,0}$, and chooses its consumption $C_t(i)$ and its wage $W_t(i)$ to maximize its utility subject to its budget constraint and the demand curve it faces for its differentiated labor. Specifically, the household solves:

$$\max_{\{C_t(i),W_t(i)\}_{t=0}^{\infty}} E_0 \sum_{t=0}^{\infty} \beta^t \frac{\left[(C_t(i) - \eta C_{t-1}(i))(\bar{L} - L_t(i))^{\zeta}\right]^{1-\sigma}}{1-\sigma}$$

$$\text{s.t. equation (17) and } L_t(i) = \left(\frac{W_t(i)}{W_t}\right)^{-\omega} \int_0^1 L_t(j)dj. \qquad (18)$$

3.6 Monetary Authority

In the spirit of the literature on monetary policy feedback reaction functions, we assume that the central bank uses the short-term interest rate as its instrument. This rate is determined in accordance with an interest rate feedback equation by which the short-term interest rate responds to deviations of inflation and economy-wide capacity utilization from their respective steady-state levels.[9] We also allow for policy inertia by including the lagged short-term interest rate in the feedback equation. In particular, monetary policy is described by

$$r_t = \phi_r r_{t-1} + \phi_\pi(\Pi_{m,t} - 1) + \phi_u \ln U_t + \epsilon_{r,t}, \qquad (19)$$

where r_t denotes the short-term interest rate (equal to $R_t - 1$), U_t denotes economy-wide capacity utilization (equal to $\int_0^1 U_t(x)dx$) and $\epsilon_{r,t}$ is an i.i.d. policy shock. Note that we have suppressed the constant that incorporates the steady-state levels of the interest rate, inflation rate, and capacity utilization rate.

3.7 Equilibrium

The decentralized (symmetric) equilibrium is an allocation:

$$\{Y_{m,t}, Y_{c,t}, Y_{i,t}, C_t, L_t, I_t, K_{t+1}, U_t\}_{t=0}^{\infty}$$

and sequences of prices:

$$\{\Pi_{m,t}, \Pi_{c,t}, \Pi_{i,t}, \Pi_{w,t}, P_{c,t}, P_{i,t}, Q_{k,t}, R_{k,t}, W_t, MC_{m,t}, R_t\}_{t=0}^{\infty}$$

that satisfy the following conditions:

[9] Capacity utilization provides a convenient proxy for the output gap without requiring any estimate of potential output.

- final-good producing firms solve (10) for $s = c$ and i;
- all materials producers solve (12), (14), and (15);
- the capitalist solves (16);
- all households solve (18);
- the monetary authority follows (19);
- all materials goods markets clear, that is equation (11) holds for all $j \in [0, 1]$;
- the consumption and capital goods markets clear $Y_{c,t} = C_t$ and $Y_{i,t} = I_t$; and,
- all factor markets clear.

Agents take as given the initial values of K_0 and R_{-1}, the sequence of values of the target variables, and the sequence of exogenous variables

$$\{A_{c,t}, A_{i,t}, A_{m,t}\}_{t=0}^{\infty}.$$

implied by the sequence of shocks

$$\{\epsilon_{c,t}, \epsilon_{i,t}, \epsilon_{m,t}, \nu_{c,t}, \nu_{i,t}, \nu_{m,t}, \epsilon_{r,t}\}_{t=0}^{\infty}.$$

The model's first-order conditions are fully described in the Appendix. In simulating the model, we normalize the variables by their balanced growth path values. The normalization is also described in the Appendix. We then log-linearize the normalized equations describing the decentralized equilibrium and solve this system using the Anderson-Moore (1985) algorithm.

4 Estimation and Calibration

All but a few of the parameters in the model outlined in sections 2 and 3 were calibrated or estimated, using minimum distance techniques, in the companion paper, Edge, Laubach, and Williams (2003). The parameters that govern the pace at which agents update their estimates of trend productivity growth were calibrated based on the findings in Edge, Laubach, and Williams (2004).

To estimate the model parameters we estimated a VAR on quarterly U.S. data using empirical counterparts to the theoretical variables in our model and identified two structural shocks using assumptions that were consistent with the theoretical model. We then chose model parameters so as to match the impulse responses to these two shocks implied by the model to those implied by the VAR.[10] The solid lines in the panels of Figure 1 show the impulse responses to our identified permanent technology shock, scaled such that the long-run response of output, its components, and the real wage are equal to 1, while Figure 2 shows the impulse responses of the variables to a funds rate shock. The dashed-dotted lines present one-standard deviation bands around the impulse responses, computed by bootstrap methods.[11] The specification of our VAR and the assumptions for identifying structural shocks are in most respects the same as those of Altig, Christiano, Eichenbaum, and Linde (2002) and our results resemble those that they obtained as well. As these authors discuss at length, a controversial result from the VAR is that hours rise in response to a positive technology shock. This finding contrasts to those of Galí (1999) and Basu, Fernald, and Kimball (1998), who find that a technology shock induces a decline in hours that lasts for a few quarters. Altig *et al.* provide evidence that one explanation for the difference between their findings and those of Galí is that in their VAR log per capita hours enter in levels, instead of in first differences. Because our model implies that per capita hours are stationary, we prefer to specify the VAR with per capita hours in levels. The estimated responses of output and its components, labor productivity, the real wage, and inflation to a funds rate shock are consistent with many other studies on the effects of monetary policy, and are very similar to those presented in Altig *et al.*

The decision as to which parameters to estimate and which ones to calibrate was (loosely) based on how informative the impulse responses are for the parameters. We calibrated those parameters, such as steady-state growth rates, that have little effect on the dynamic responses to shocks and estimated the remaining parameters by minimizing the squared

[10]Recent applications of this estimation strategy are Rotemberg and Woodford (1997), Amato and Laubach (2003), Christiano, Eichenbaum, and Evans (2003), and Altig, Christiano, Eichenbaum, and Linde (2002). Details on our estimation procedure can be found in the appendix at the end of the paper, which reproduces the VAR specification and identification section from Edge, Laubach, and Williams (2003).

[11]To prevent the standard error bands from diverging over time, we discard those draws for which the implied reduced-form VAR was estimated to be unstable. Specifically, we discard those draws for which the largest eigenvalue of the coefficient matrix in the reduced form, written in companion form, exceeds .995, which is the case for about 15 percent of all draws.

deviations of the responses from the model and the VAR of eight variables to two identified shocks.

The calibrated model parameters are shown in the upper panel of Table 1. All growth, depreciation, inflation, and interest rates along with the rate of time preference β are expressed at annual rates. The endowment $\bar{L}$ is normalized to 1. The value $\alpha = .3$ is consistent with an average labor share in the nonfarm business sector over 1952q1 to 2000q4 of .64 under the assumption of a 10 percent markup in intermediate goods markets (which is a bit lower than our markup estimate, see below). The value of δ is compatible with our use of a comprehensive measure of capital including residential and nonresidential structures. The gross growth rate Γ_m in the intermediate goods sector is unobserved, and hence we normalize it to 1. The growth rates Γ_c and Γ_i are based on the average growth rates of our consumption and investment aggregates over the period 1960q1 to 2001q4, which are 3.1 percent and 5.7 percent respectively. The steady-state inflation rate in one sector has to be calibrated; given our assumptions about growth rates in the various sectors, the inflation rate in one sector determines the inflation rates in the others, as well as wage inflation. We choose to calibrate inflation in the consumption sector to 2 percent at an annual rate.

The estimated parameters are shown in the middle panel of the table, with standard errors in parentheses. Standard errors are computed using the Jacobian matrix from the numerical optimization routine and the empirical estimate of the covariance matrix of the impulse responses from the bootstrap. The coefficients of the model are generally estimated with good precision.

One feature of both sets of impulse responses is that real investment, hours, and utilization display prolonged hump-shaped responses to the shocks. Consumption follows a similar pattern in the response to the monetary policy shock, but monotonically rises to its new level in response to the technology shock. In the case of a permanent technology shock, Rotemberg and Woodford (1996) demonstrated that DGE models without intrinsic inertia will not display such hump-shaped patterns; instead, these variables jump on impact and adjust monotonically to their new steady-state values.

Not surprisingly, in estimating the model, we find a significant role for inertia in consumption (in the form of habit persistence) and in investment (in the form of adjustment costs) is needed to match these moments. Our estimate of the habit parameter η is close to the value estimated by Boldrin, Christiano, and Fisher (2001), Smets and Wouters (2002),

Table 1: Structural Parameter Estimates

	Preferences		Technology		Growth		Prices		Policy	
Calibrated	β	.97	α	.3	$\bar{\Gamma}_m$	1	$\bar{\Pi}_c$	1.02		
	$\bar{L}$	1	δ	.10	$\bar{\Gamma}_i$	1.06				
					$\bar{\Gamma}_c$	1.03				
Estimated	σ	2.79	θ	5.41			$\chi_{p,1}$	32.45	ϕ_r	.78
		(.49)		(1.46)				(13.69)		(.01)
	ζ	2.43	ω	4.00			$\chi_{p,2}$	.002	ϕ_π	.49
		(5.16)		(1.83)				(1.52)		(.04)
	η	.64	ψ	.77			$\chi_{w,1}$	291	ϕ_u	.005
		(.02)		(.07)				(47.21)		(.002)
			χ_i	1.75			$\chi_{w,2}$	262		
				(.30)				(49.12)		

and Christiano, Eichenbaum, and Evans (2003), but smaller than the estimate reported in Fuhrer (2000). Our estimate of χ_i, the adjustment cost parameter in investment, is smaller than the value of 3.60 reported in Christiano *et al.*, or 6.77 reported in Smets and Wouters. Still, this degree of inertia in investment is sufficient to deliver the distinctive hump-shaped response of investment seen implied by the data.

A second noteworthy feature of the impulse responses is the difference of the impulse responses of inflation to the two shocks. Interestingly, in response to the technology shock inflation drops on impact and then returns to steady state relatively quickly. In contrast the response of inflation to the monetary policy shock is gradual and persistent, suggesting inflation inertia or some other deviation from standard price-setting models. For the price equation, our estimates imply no intrinsic inflation inertia with the estimated value of $\chi_{p,2}$ being near zero, reflecting the response to the technology shock. In contrast, we find evidence of intrinsic nominal wage inflation inertia, as evidenced by the estimated value of $\chi_{w,2}$ exceeding 100 with an estimated standard error of about 25.

Rounding out the remainder of the estimates, we find a value of σ well above unity.The estimated aggregate labor supply elasticity, based on our estimate of ζ, is above 4, higher than micro-based studies but consistent with other macro-based estimates. The values of θ and ω imply steady-state markups in intermediate goods and labor markets of 23 percent and 33 percent, respectively. Our estimate of the elasticity of the utilization cost function ψ

implies greater costs from variations in capital utilization than the estimates of Christiano *et al.* (2001), Altig *et al.* (2002), or Smets and Wouters (2002) do, although some of the difference between our estimate and others may be due to alternative formulations of utilization costs used in those studies. Our estimates of the parameters of the monetary policy rule, ϕ_r, ϕ_π, and ϕ_u, are broadly consistent with the findings of many other studies that estimate monetary policy reaction functions, such as that of Clarida, Galí, and Gertler (2000).

The dashed lines in Figure 1 present the impulse responses implied by the model under our parametrization to a permanent unanticipated increase in technology that raises $y_{m,t}, c_t, i_t, l_t$, and w_t in the long run by one percent. Figure 2 shows the responses to a one percentage point shock to the funds rate, computed under the assumption that no other variable can respond contemporaneously to this shock. The model matches the responses to the technology shock very well across the board. Compared to the VAR impulse responses, the model impulse responses to a funds rate shock of $y_{m,t}, c_t, i_t, l_t$, and $\pi_{m,t}$ are of approximately same magnitude, but appear to be front-loaded, in that the VAR impulse responses reach their trough several quarters after the model responses.

The parameter that governs the pace at which agents update their estimates of trend productivity growth, specifically the gain λ, is set equal to 0.025 per quarter in our model. This was the value that in Edge, Laubach, and Williams (2004) was found to replicate quite well real time estimates of long-run labor productivity growth given real time labor productivity data. This calibration implies that if MFP growth increase in any period, agents will interpret most—that is, 97.5 percent—of it as being transitory so that only a small fraction—2.5 percent—will be reflected in higher underlying MFP growth. As a result, a transitory shock to MFP growth will, for the most part, be recognized correctly. In contrast a persistent MFP growth rate shock will for a long time be incorrectly interpreted as transitory.

5 Monetary Policy and Technology Shocks

In this section, we analyze the impulse responses to four types of technology shocks under different monetary policy assumptions. In the following, we make two small adjustments to the model. First, we set $\Gamma_c = 1$. Second, we assume that the estimate monetary policy rule responds to the difference between the utilization rate of capital and its natural rate associated with the flexible wage and price equilibrium. The latter adjustment is needed for simulations of persistent shocks to the growth rate which yield sustained movements in the natural rate of utilization. Finally, we incorporate a time-varying neutral rate of interest in the monetary policy rule that incorporates the long-run effects of a change in the growth rate on the neutral real interest rate.[12]

5.1 Methodology

We compute the optimal Ramsey policy using the methods of Levin and Lopez-Salido (2004) and the software package DYNARE.

5.2 Monetary Policy and Sector-neutral Technology Shocks

A permanent increase to the level of sector-neutral MFP: The first shock that we consider is the same as was used to estimate the model, namely an unanticipated permanent increase in the level of sector-neutral technology. The dashed lines in Figure 3 report the economy's response to this shock under the model's estimated policy rule. These responses are almost exactly the same as those shown in by the dashed lines in Figure 1, with the small differences arise from the modified assumptions described above.

The allocation of resources under the optimal monetary policy is nearly the same as in the flexible wage and price economy. The solid lines in Figure 3 represent the economy's response to an unanticipated permanent increase in the level of sector-neutral technology under the optimal policy under commitment (that is, the solution to the Ramsey problem). The dotted-dashed lines in Figure 3 show the response to an unanticipated permanent increase in the level of sector-neutral technology in an economy that is identical to our estimated model with the exception of having completely flexible prices and wages. Hours briefly decline in response to the shock and then turn mildly positive. Capital utilization rises in response to the shock and remains elevated for over a decade.

The optimal policy holds wage inflation near its steady-state value. The increase in productivity eventually elicits an equal increase in the real wage. Owing to the larger costs of adjustments to changing wages relative to prices, this rise in the real wage is almost entirely accomplished through a decline in the price level, leaving nominal wages nearly

[12] We add a term $(1-\phi_r)\sigma g_t$ to the policy rule, where g_t is the perceived trend growth rate of sector-neutral MFP.

constant.

Compared to the Ramsey policy, the estimated policy rule generates excessively large increases in hours, utilization, consumption, and investment. Inflation initially falls, but then overshoots the steady-state level after a few periods.

A persistent observable increase the growth-rate of sector-neutral MFP: We now consider the economy's response to technology growth rate shocks first under the assumption that agents immediately recognize the increase in the level of technology as being the result of a growth rate shock. The dashed lines in Figure 4 report the economy's response to a very persistent increase in the growth-rate of sector-neutral technology growth, with autocorrelation coefficient of 0.95.

As noted by Campbell (1994) stochastic growth models with flexible wages and prices predict a decline in investment, hours, and output following a highly persistent positive shock to the growth rate of technology owing to the dominate wealth effects associated with such a shock. This pattern is seen in the impulse responses of our model shown in Figure 4. It is worth stressing, however, that in a sticky wage and price model, the initial response to such a shock depends crucially on the monetary policy rule in place. Under a different policy rule, the model can yield positive initial responses of hours, output, and even inflation.

As in the case of the level shock to technology, the optimal policy achieves the increase in real wages called forth by more rapid productivity growth primarily by suppressing the rate of price inflation. It generates this through a very large increase in nominal (and real) interest rates which restrains aggregate demand following the productivity growth rate shock. As a result, the paths for hours and output are slightly below those resulting from the flexible-wage and price economy.

A persistent unobservable persistent increase the growth-rate of sector-neutral MFP: We now consider the economy's response to technology growth rate shocks under the assumption that agents can observe only the level of technology and must infer the transitory and persistent components of the shock. All agents are assumed to know the process underlying productivity growth and update their estimates using the Kalman filter, that is, they follow the updating rule given by equation (8).

As in the previous cases, the optimal policy yields an allocation of resources close to that resulting from the flexible wage and price economy and holds nominal wages close to the steady-state values. Hours move relatively little, while utilization rises gradually. Investment growth rises for a short time, then is basically constant at its baseline value for the remainder of the decade. The optimal inflation rate falls by about 0.7 percentage points and remains below baseline for more than ten years. The optimal policy response is a large initial decline in the in interest rate. The interest rate then rises very gradually.

The swings in hours, consumption, and investment under the estimated rule are much larger than in under the optimal policy. The decline in inflation is smaller than under the optimal policy, but just as persistent.

Finally, we consider a permanent increase in the growth rate of sector-neutral MFP. The results are shown in Figure 5 and are very similar to those of a highly persistent shock to the growth rate.

6 Conclusion

We find that the optimal policy response to technology shocks achieves a real allocation close to that in the flexible wage and price equilibrium and forces resulting movements in the real wage onto the movements in price inflation, leaving wage inflation nearly constant. As a result, sustained shifts in the growth rate of productivity result in sustained movements in price inflation in the opposite direction, consistent with the experience of the 1970s and late 1990s. We find a similar pattern under the estimated policy rule, but in that case, the real allocation responds excessively to technology shocks.

In this paper, we analyze a basic question for monetary policy: should the central bank raise or lower interest rates, and by how much, in response to an increase in the productivity? The answer, not surprisingly, is that, "It depends." In particular, it depends crucially on whether the shock to productivity growth is perceived to be permanent or temporary. In the former case, the optimal response is to raise interest rates; in the latter, it is to lower them.

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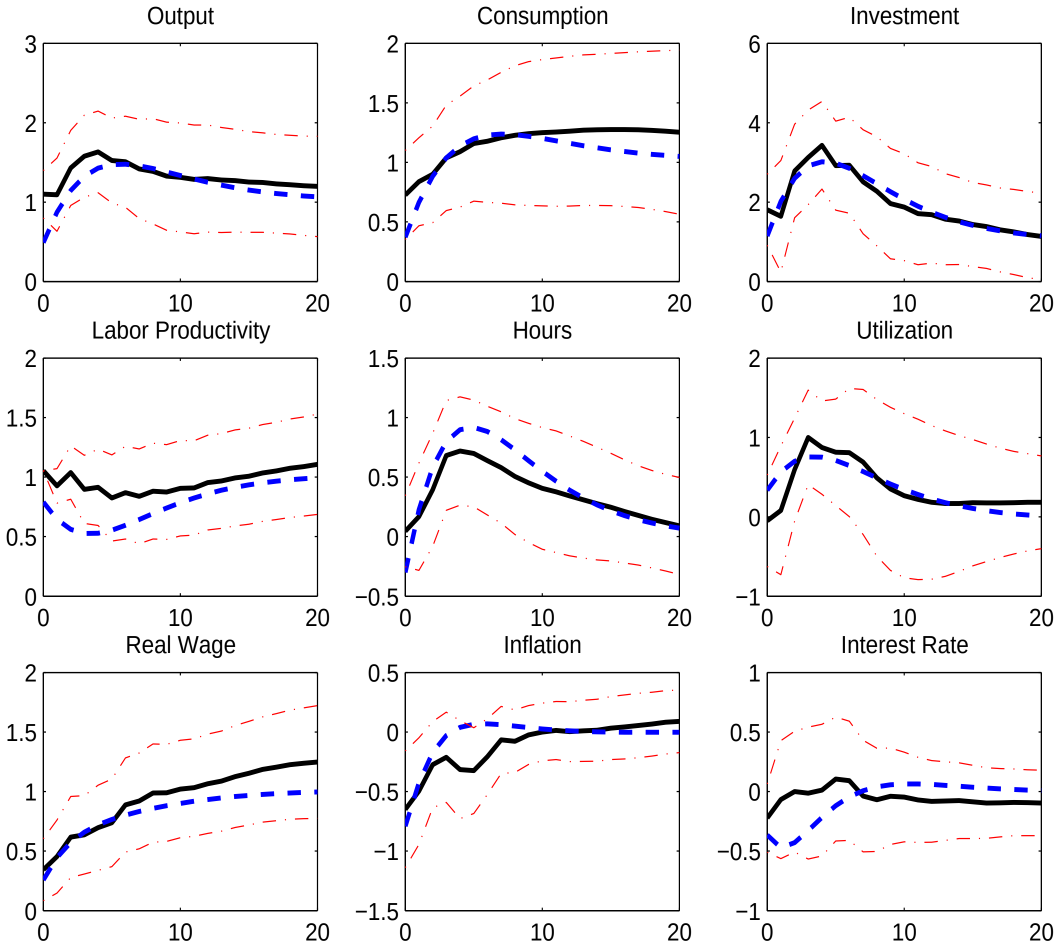
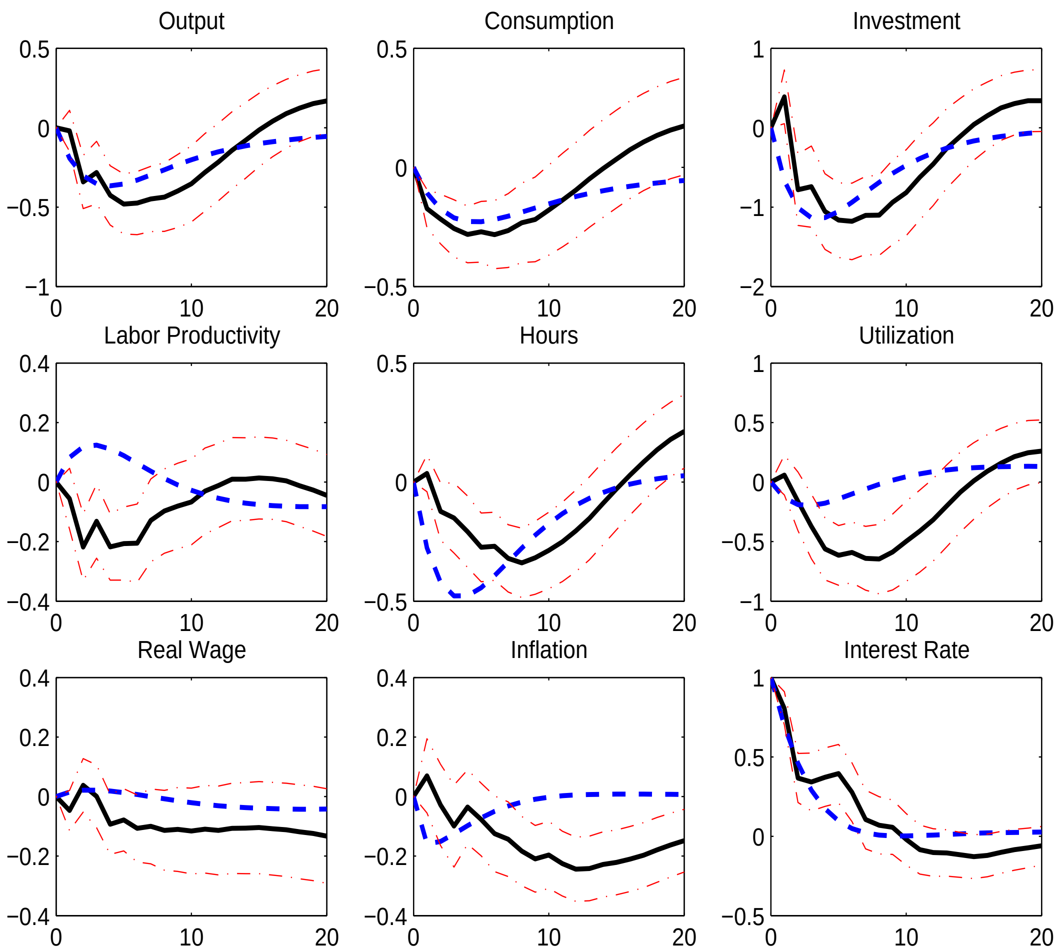
Figure 1: VAR and Model Impulse Responses to a Technology Shock



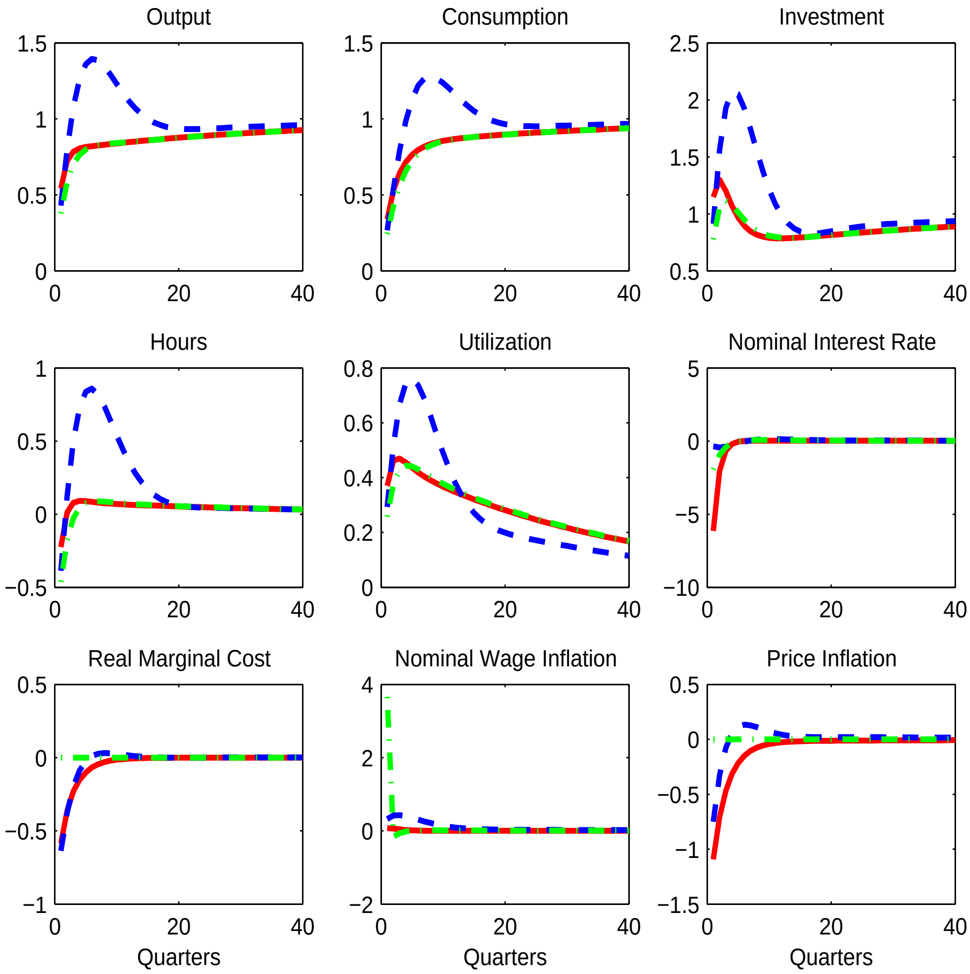
Notes: The solid lines show the impulse responses implied by the VAR to an identified technology shock that in the long-run raises output and its components by one percent. The dashed lines show the impulse responses implied by the model to a permanent one-percent shock to technology in sector m. The dashed-dotted lines are one standard error confidence intervals around the VAR responses.

Figure 2: VAR and Model Impulse Responses to a Funds Rate Shock



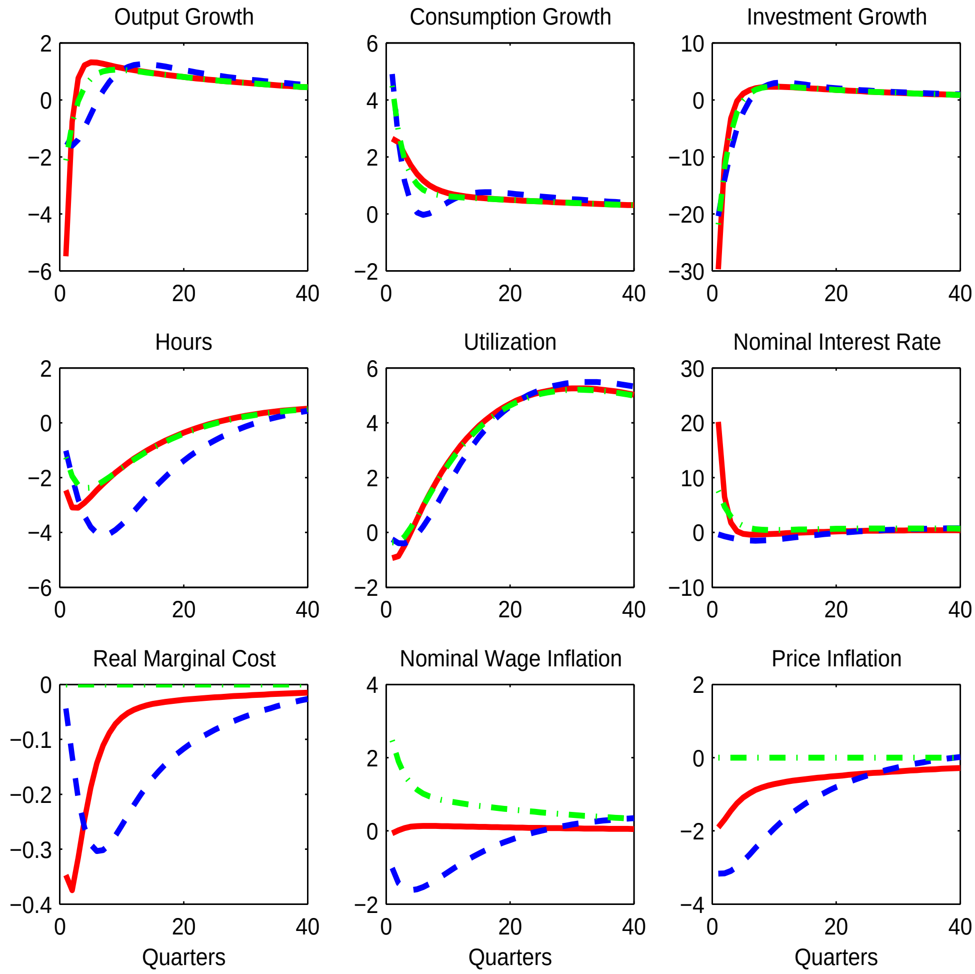
Notes: The solid lines show the impulse responses implied by the VAR following a one percent funds rate shock. The dashed lines show the impulse responses implied by the model to the same shock under the assumption that the contemporaneous response of all variables other than the funds rate is zero. The dashed-dotted lines are one standard error confidence intervals around the VAR responses.

Figure 3: Response to a sector-neutral MFP level shock



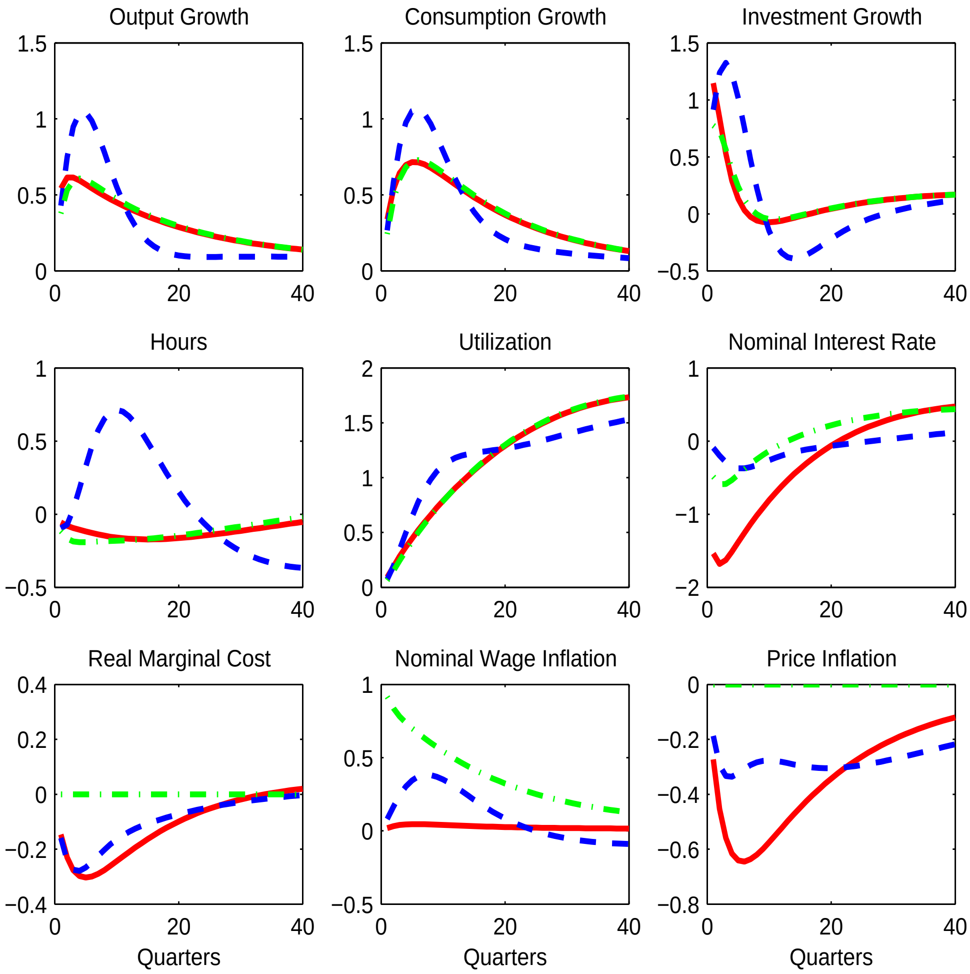
Notes: The solid lines show the impulse responses assuming the monetary authority follows the optimal policy. The dashed lines show the impulse responses implied by the estimated policy rule. The dashed-dotted the impulse responses in the flexible wage and price version of the model.

Figure 4: Response to a Persistent Increase in MFP Growth



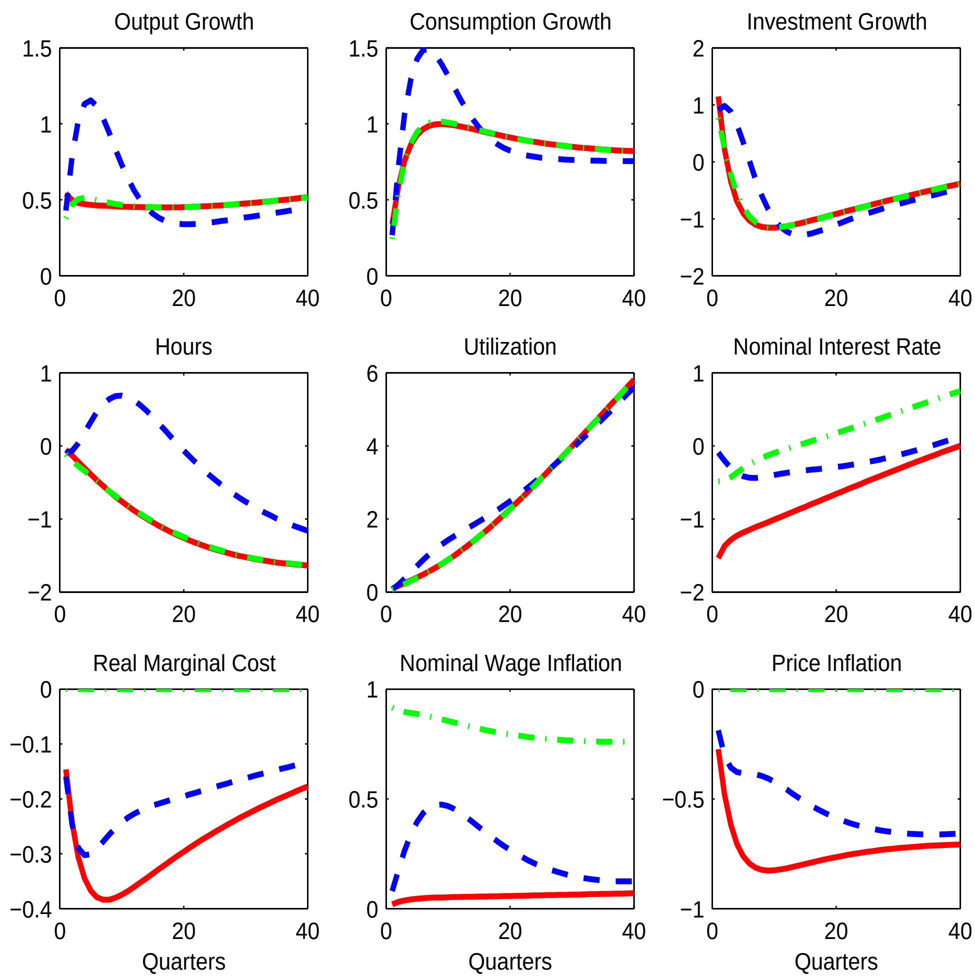
Notes: The solid lines show the impulse responses assuming the monetary authority follows the optimal policy. The dashed lines show the impulse responses implied by the estimated policy rule. The dashed-dotted the impulse responses in the flexible wage and price version of the model.

Figure 5: Response to a Persistent Increase in MFP Growth with Learning



Notes: The solid lines show the impulse responses assuming the monetary authority follows the optimal policy. The dashed lines show the impulse responses implied by the estimated policy rule. The dashed-dotted the impulse responses in the flexible wage and price version of the model.

Figure 6: Response to a Permanent Increase in MFP Growth with Learning



Notes: The solid lines show the impulse responses assuming the monetary authority follows the optimal policy. The dashed lines show the impulse responses implied by the estimated policy rule. The dashed-dotted the impulse responses in the flexible wage and price version of the model.

Model Appendix

In this appendix, we derive and log-linearize the first-order conditions and describe the normalization of variables along the balanced growth path.

First-order Conditions

The consumption and capital goods producing firms' cost minimization problems (equation 10 for $s = c$ and i) yield demand functions from each final-good producing sector for each of the intermediate goods:

$$Y_{m,c,t}(j) = \left(\frac{P_{m,t}(j)}{P_{m,t}}\right)^{-\theta} \frac{Y_{c,t}}{A_{c,t}^{1-\alpha}} \text{ and } Y_{m,i,t}(j) = \left(\frac{P_{m,t}(j)}{P_{m,t}}\right)^{-\theta} \frac{Y_{i,t}}{A_{i,t}^{1-\alpha}} \tag{20}$$

where the variable $P_{m,t}$, which has the interpretation of being the competitive price for the cost-minimizing bundle of materials goods, is defined:

$$P_{m,t} = \left(\int_0^1 \left(P_{m,t}(j)\right)^{1-\theta} dj\right)^{\frac{1}{1-\theta}}. \tag{21}$$

The demand functions in equation (20) imply an economy-wide demand for each intermediate good of:

$$Y_{m,t}(j) = Y_{m,c,t}(j) + Y_{m,i,t}(j) = \left(\frac{P_{m,t}(j)}{P_{m,t}}\right)^{-\theta} \left(\frac{Y_{c,t}}{A_{c,t}^{1-\alpha}} + \frac{Y_{i,t}}{A_{i,t}^{1-\alpha}}\right). \tag{22}$$

In the symmetric equilibria that we consider (that is, where $P_{m,t}(j) = P_{m,t}$ for all j) this demand function simplifies to:

$$Y_{m,t}(j) = \left(\frac{Y_{c,t}}{A_{c,t}^{1-\alpha}} + \frac{Y_{i,t}}{A_{i,t}^{1-\alpha}}\right). \tag{23}$$

The competitive prices of consumption and capital goods are:

$$P_{c,t} = P_{m,t} A_{c,t}^{-(1-\alpha)} \text{ and } P_{i,t} = P_{m,t} A_{i,t}^{-(1-\alpha)}. \tag{24}$$

The capitalists profit-maximization problem (equation 16) yields the following first-order conditions:

$$\begin{aligned} P_{i,t} I_t = {} & \exp\left[-\frac{\chi_i}{2}\left(\frac{I_t}{I_{t-1}} - \Gamma_i\right)^2\right]\left(1 - \chi_i \frac{I_t}{I_{t-1}}\left(\frac{I_t}{I_{t-1}} - \Gamma_i\right)\right) Q_{k,t} I_t \\ & + \beta E_t\left[\frac{\Lambda_{c,t+1}/P_{c,t+1}}{\Lambda_{c,t}/P_{c,t}} \exp\left[-\frac{\chi_i}{2}\left(\frac{I_{t+1}}{I_t} - \Gamma_i\right)^2\right] \chi_i \frac{I_{t+1}}{I_t}\left(\frac{I_{t+1}}{I_t} - \Gamma_i\right) Q_{k,t+1} I_{t+1}\right] \end{aligned} \tag{25}$$

$$Q_{k,t} = \beta E_t\left[\frac{\Lambda_{c,t+1}/P_{c,t+1}}{\Lambda_{c,t}/P_{c,t}} \left(\left(\left(1-\delta\right) Q_{k,t+1} + R_{k,t+1}\right)\right)\right] \tag{26}$$

The household's utility-maximization problem (equation 18) yields an Euler equation and labor supply schedules. In a symmetric equilibrium, all households make the same consumption and wage decisions. Hence the index i is dropped in the following. Letting $\Lambda_{c,t}$ denote the marginal utility of consumption we define

$$\Lambda_{c,t} = (C_t - \eta C_{t-1})^{-\sigma} (\bar{L} - L_t)^{\zeta(1-\sigma)} - E_t \beta \eta \left[(C_{t+1} - \eta C_t)^{-\sigma} (\bar{L} - L_{t+1})^{\zeta(1-\sigma)} \right]. \tag{27}$$

Letting $\Lambda_{l,t}$ denote the marginal disutility of labor supply we define

$$\Lambda_{l,t} = \zeta \left(C_t - \eta C_{t-1}\right)^{(1-\sigma)} \left(\bar{L} - L_t\right)^{\zeta(1-\sigma)-1}. \tag{28}$$

This allows us to write the Euler equation as

$$\frac{\Lambda_{c,t}}{P_{c,t}} = \beta R_t E_t \left[\frac{\Lambda_{c,t+1}}{P_{c,t+1}} \right] \tag{29}$$

and the labor supply curve as:

$$\begin{aligned} \frac{\Lambda_{l,t}}{\Lambda_{c,t}} L_t \omega = {} & (\omega - 1)(1 + \varsigma_\omega) \frac{W_t}{P_{c,t}} L_t + \left(\chi_{w,1} \left(\Pi_{w,t} - \Pi_w\right) \Pi_{w,t} + \chi_{w,2} \left(\frac{\Pi_{w,t}}{\Pi_{w,t-1}} - 1 \right) \frac{\Pi_{w,t}}{\Pi_{w,t-1}} \right) \frac{W_t}{P_{c,t}} L_t \\ & - \beta E_t \left[\frac{\Lambda_{c,t+1}}{\Lambda_{c,t}} \left(\chi_{w,1} \left(\Pi_{w,t+1} - \Pi_w\right) \Pi_{w,t+1} + 2\chi_{w,2} \left(\frac{\Pi_{w,t+1}}{\Pi_{w,t}} - 1 \right) \frac{\Pi_{w,t+1}}{\Pi_{w,t}} \right) \frac{W_{t+1}}{P_{c,t+1}} L_{t+1} \right] \\ & + \beta^2 E_t \left[\frac{\Lambda_{c,t+2}}{\Lambda_{c,t+1}} \frac{\Lambda_{c,t+1}}{\Lambda_{c,t}} \left(\chi_{w,2} \left(\frac{\Pi_{w,t+2}}{\Pi_{w,t+1}} - 1 \right) \frac{\Pi_{w,t+2}}{\Pi_{w,t+1}} \right) \frac{W_{t+2}}{P_{c,t+2}} L_{t+2} \right] \end{aligned} \tag{30}$$

The first step of the intermediate-good producing firm's cost-minimization problem equation (12) implies an economy-wide demand schedule for type i labor of:

$$L_t(i) = \int_0^1 L_t(i,j) dj = \left(\frac{W_t(j)}{W_t} \right)^{-\omega} \int_0^1 L_t(j) dj = \left(\frac{W_t(j)}{W_t} \right)^{-\omega} L_t. \tag{31}$$

In the symmetric equilibrium this equation implies that $L_t(i) = L_t$ for all i. The second step of the intermediate-good producing firm's cost-minimization problem equation (14) implies the following first-order conditions:

$$\alpha \frac{(K_t U_t)^\alpha (A_{m,t} L_t)^{1-\alpha}}{K_t} = \frac{R_{k,t}}{MC_{m,t}} + \Psi(U_t)(A_{i,t})^{-(1-\alpha)} \tag{32}$$

$$(1-\alpha) \frac{(K_t U_t)^\alpha (A_{m,t} L_t)^{1-\alpha}}{L_t} = \frac{W_t}{MC_{m,t}} \tag{33}$$

$$\alpha \frac{(K_t U_t)^\alpha (A_{m,t} L_t)^{1-\alpha}}{K_t U_t} = \Psi'(U_t)(A_{i,t})^{-(1-\alpha)} \tag{34}$$

$$(K_t U_t)^\alpha (A_{m,t} L_t)^{1-\alpha} = Y_{m,t} + K_t \Psi(U_t)(A_{i,t})^{-(1-\alpha)}. \tag{35}$$

Together these equation imply capital and labor factor demand schedules, an expression for optimal utilization and a marginal cost schedule. The intermediate-good producing firm's profit-maximization problem equation (15) implies a price Phillips curve of:

$$
\begin{aligned}
& MC_{m,t} Y_{m,t} \theta \\
& = (\theta - 1)(1 + \varsigma_\theta) P_{m,t} Y_{m,t} + \left(\chi_{p,1} (\Pi_{m,t} - \Pi_m) \Pi_{m,t} + \chi_{p,2} \left(\frac{\Pi_{m,t}}{\Pi_{m,t-1}} - 1 \right) \frac{\Pi_{m,t}}{\Pi_{m,t-1}} \right) P_{m,t} Y_{m,t} \\
& - \beta E_t \left[\frac{\Lambda_{c,t+1}/P_{c,t+1}}{\Lambda_{c,t}/P_{c,t}} \right. \\
& \qquad \left. \times \left(\chi_{p,1} (\Pi_{m,t+1} - \Pi_m) \Pi_{m,t+1} + 2\chi_{p,2} \left(\frac{\Pi_{m,t+1}}{\Pi_{m,t}} - 1 \right) \frac{\Pi_{m,t+1}}{\Pi_{m,t}} \right) P_{m,t+1} Y_{m,t+1} \right] \\
& + \beta^2 E_t \left[\frac{\Lambda_{c,t+2}/P_{c,t+2}}{\Lambda_{c,t+1}/P_{c,t+1}} \frac{\Lambda_{c,t+1}/P_{c,t+1}}{\Lambda_{c,t}/P_{c,t}} \left(\chi_{p,2} \left(\frac{\Pi_{m,t+2}}{\Pi_{m,t+1}} - 1 \right) \frac{\Pi_{m,t+2}}{\Pi_{m,t+1}} \right) P_{m,t+2} Y_{m,t+2} \right].
\end{aligned}
\tag{36}
$$

Balanced Growth

The first step required in specifying the first-order conditions in terms of stationary variables only is to determine the rates of growth of the non-stationary variables. From equation (2) we know that in the steady state:

$$\ln \Gamma_m = (1 - \alpha) \ln \Gamma_{a,m} + \alpha \ln \Gamma_i \tag{37}$$

where $\bar{\Gamma}_m$ is the steady-state growth rate of materials goods *production*, while $\bar{\Gamma}_{a,m}$ is the steady-state growth rate of *technology* in the materials production function. $\bar{\Gamma}_i$ is the steady-state growth rate of investment goods production, which is defined from equation (1) for $s = i$ as:

$$\ln \Gamma_i = (1 - \alpha) \ln \Gamma_{a,i} + \ln \Gamma_{a,m} \tag{38}$$

while $\bar{\Gamma}_c$ is the steady-state growth rate of consumption goods production, which is defined from equation (1) for $s = c$ as:

$$\ln \Gamma_c = (1 - \alpha) \ln \Gamma_{a,c} + \ln \Gamma_m. \tag{39}$$

Equations (37) and (38), can be solved simultaneously to yield

$$\ln \Gamma_m = \ln \Gamma_{a,m} + \alpha \ln \Gamma_{a,i} \text{ and} \tag{40}$$

$$\ln \Gamma_{a,i} = \ln \Gamma_{a,m} + \ln \Gamma_{a,i}, \tag{41}$$

which then allows us to re-write equation (39):

$$\ln \Gamma_c = \ln \Gamma_{a,m} + \alpha \ln \Gamma_{a,i} + (1-\alpha) \ln \Gamma_{a,c}. \tag{42}$$

Equations (40) to (42) imply that the following renormalized product market quantity variables are stationary:

$$\widetilde{Y}_{m,t} = \frac{Y_{m,t}}{A_{m,t}A_{i,t}^{\alpha}}, \widetilde{Y}_{i,t} = \frac{Y_{i,t}}{A_{m,t}A_{i,t}}, \widetilde{Y}_{c,t} = \frac{Y_{c,t}}{A_{m,t}A_{i,t}^{\alpha}A_{c,t}^{1-\alpha}}, \widetilde{I}_t = \frac{I_t}{A_{m,t}A_{i,t}}, \text{ and } \widetilde{C}_t = \frac{C_t}{A_{m,t}A_{i,t}^{\alpha}A_{c,t}^{1-\alpha}}. \tag{43}$$

In factor markets, labor input L_t is stationary without any renormalization. Capital is rendered stationary by the following renormalization:

$$\widetilde{K}_t = \frac{K_t}{A_{m,t}A_{i,t}}. \tag{44}$$

This normalization implies that while the unnormalized $t+1$ capital stock K_{t+1} is known in period t, the normalized $t+1$ capital stock $\widetilde{K}_{t+1}$ is not known until $A_{m,t+1}$ and $A_{i,t+1}$ are realized in period $t+1$. From the equations in (21) and (24) we know that in steady state

$$\ln \Pi_m(j) = \ln \Pi_m, \ln \Pi_c = \ln \Pi_m - (1-\alpha) \ln \Gamma_{a,c}, \text{ and } \ln \Pi_k = \ln \Pi_m - (1-\alpha) \ln \Gamma_{a,i} \tag{45}$$

where Π_m is the steady-state aggregate inflation rate in the materials good sector, $\Pi_m(j)$ is the steady-state inflation rate for the jth materials goods, and Π_c and Π_i are the steady-state inflation rates for consumption and capital goods prices. These conditions imply that the following product price ratios are stationary:

$$\widetilde{P}_{m,t}(j) = \frac{P_{m,t}(j)}{P_{m,t}}, \widetilde{P}_{c,t} = \frac{P_{c,t}}{P_{m,t}}A_{c,t}^{1-\alpha}, \widetilde{P}_{i,t} = \frac{P_{i,t}}{P_{m,t}}A_{i,t}^{1-\alpha}, \text{ and } \widetilde{Q}_t = \frac{Q_{k,t}}{P_{m,t}}A_{i,t}^{1-\alpha}. \tag{46}$$

The capitalists supply schedule, equation (26), implies that the steady-state nominal growth rate of the rental rate on capital is equal to the steady-state capital price inflation rate (that is, $\ln \Pi_{R_k} = \ln \Pi_i$). The steady-state growth rate of nominal wages, can be inferred from equation (30), which states that it is equal to

$$\ln \Pi_w(i) = \ln \Pi_w = \ln \Pi_m + \ln \Gamma_{a,m} + \alpha \ln \Gamma_{a,i}. \tag{47}$$

Consequently, the following real factor prices are also stationary:

$$\widetilde{W}_t(i) = \frac{W_t(i)}{P_{m,t}A_{m,t}A_{i,t}^{\alpha}}, \widetilde{W}_t = \frac{W_t}{P_{m,t}A_{m,t}A_{i,t}^{\alpha}}, \text{ and } \widetilde{R}_{k,t} = \frac{R_{k,t}}{P_{m,t}}A_{i,t}^{1-\alpha}, \tag{48}$$

while stationary marginal cost is

$$\widetilde{MC}_{m,t}(j) = \frac{MC_{m,t}}{P_{m,t}} \tag{49}$$

.

Finally it is worth noting from equation (27) that we can perform the following renormalization to make the marginal utility of consumption $\Lambda_{c,t}$ stationary

$$\widetilde{\Lambda}_{c,t} = \frac{\Lambda_{c,t}}{A_{m,t}^{-\sigma} A_{i,t}^{-\sigma\alpha} A_{c,t}^{-\sigma(1-\alpha)}}. \tag{50}$$

and while from equation (28) we can make the marginal utility of labor $\Lambda_{h,t}$ stationary with:

$$\widetilde{\Lambda}_{l,t} = \frac{\Lambda_{h,t}}{A_{m,t}^{(1-\sigma)} A_{i,t}^{(1-\sigma)\alpha} A_{c,t}^{(1-\sigma)(1-\alpha)}}. \tag{51}$$

First-Order Conditions (with Stationary Variables Only)

The consumption and capital goods producing firms' cost minimization problems imply a (stationary) economy-wide demand for each intermediate good of:

$$\widetilde{Y}_{m,t}(j) = \widetilde{Y}_{c,t}(j) + \widetilde{Y}_{i,t}(j) = \left(\widetilde{P}_{m,t}(j)\right)^{-\theta} \left(\widetilde{Y}_{c,t} + \widetilde{Y}_{i,t}\right) \tag{52}$$

which in the symmetric equilibrium is:

$$\widetilde{Y}_{m,t} = \widetilde{Y}_{m,t}(j) = \widetilde{Y}_{c,t}(j) + \widetilde{Y}_{i,t}(j) = \widetilde{Y}_{c,t} + \widetilde{Y}_{i,t}. \tag{53}$$

The stationary relative prices of the consumption and capital goods are:

$$\widetilde{P}_{c,t} = 1 \text{ and } \widetilde{P}_{i,t} = 1. \tag{54}$$

The capitalists profit-maximization problem (equation 16) yields the following (stationary) first-order conditions:

$$\begin{aligned} \widetilde{I}_t = \exp\left[-\frac{\chi_i}{2}\left(\frac{\widetilde{I}_t}{\widetilde{I}_{t-1}}\Gamma_{i,t}-\Gamma_i\right)^2\right]\left(1-\chi_i\frac{\widetilde{I}_t}{\widetilde{I}_{t-1}}\Gamma_{i,t}\left(\frac{\widetilde{I}_t}{\widetilde{I}_{t-1}}\Gamma_{i,t}-\Gamma_i\right)\right)\frac{\widetilde{Q}_{k,t}}{\widetilde{P}_{i,t}}\widetilde{I}_t \\ + \beta E_t\left[\frac{\widetilde{\Lambda}_{c,t+1}}{\widetilde{\Lambda}_{c,t}}\frac{\Pi_{i,t+1}}{\Pi_{c,t+1}}\left(\Gamma_{c,t+1}\right)^{-\sigma}\exp\left[-\frac{\chi_i}{2}\left(\frac{\widetilde{I}_{t+1}}{\widetilde{I}_t}\Gamma_{i,t}-\Gamma_i\right)^2\right]\right. \\ \left.\times\chi_i\frac{\widetilde{I}_{t+1}}{\widetilde{I}_t}\Gamma_{i,t+1}\left(\frac{\widetilde{I}_{t+1}}{\widetilde{I}_t}\Gamma_{i,t+1}-\Gamma_i\right)\frac{\widetilde{Q}_{k,t+1}}{\widetilde{P}_{i,t+1}}\Gamma_{i,t+1}\widetilde{I}_{t+1}\right] \end{aligned} \tag{55}$$

$$\frac{\widetilde{Q}_{k,t}}{\widetilde{P}_{i,t}} = \beta E_t\left[\frac{\widetilde{\Lambda}_{c,t+1}}{\widetilde{\Lambda}_{c,t}}\frac{\Pi_{i,t+1}}{\Pi_{c,t+1}}\left(\Gamma_{c,t+1}\right)^{-\sigma}\left((1-\delta)\frac{\widetilde{Q}_{k,t+1}}{\widetilde{P}_{i,t+1}} + \frac{\widetilde{R}_{k,t+1}}{\widetilde{P}_{i,t+1}}\right)\right] \tag{56}$$

The stationary version of the capital evolution equation is:

$$\Gamma_{i,t+1}\widetilde{K}_{t+1} = (1-\delta)\,\widetilde{K}_t + \widetilde{I}_t \tag{57}$$

The Euler equation and labor supply schedule (equations 29 and 30) from the households utility-maximization problem is:

$$\widetilde{\Lambda}_{c,t} = \beta E_t\left[\left(\frac{R_t}{\Pi_{c,t+1}}\left(\Gamma_{c,t+1}\right)^{-\sigma}\widetilde{\Lambda}_{c,t+1}\right)\right] \tag{58}$$

and the labor supply curve as:

$$\begin{aligned}
\frac{\widetilde{\Lambda}_{l,t}}{\widetilde{\Lambda}_{c,t}}L_t\omega = &(\omega-1)\left(1+\varsigma_\omega\right)\frac{\widetilde{W}_t}{\widetilde{P}_{c,t}}L_t + \left(\chi_{w,1}\left(\Pi_{w,t}-\Pi_w\right)\Pi_{w,t} + \chi_{w,2}\left(\frac{\Pi_{w,t}}{\Pi_{w,t-1}}-1\right)\frac{\Pi_{w,t}}{\Pi_{w,t-1}}\right)\frac{\widetilde{W}_t}{\widetilde{P}_{c,t}}L_t \\
&-\beta E_t\Bigg[\frac{\widetilde{\Lambda}_{c,t+1}}{\widetilde{\Lambda}_{c,t}}\left(\Gamma_{c,t+1}\right)^{-\sigma} \\
&\quad\times\left(\chi_{w,1}\left(\Pi_{w,t+1}-\Pi_w\right)\Pi_{w,t+1} + 2\chi_{w,2}\left(\frac{\Pi_{w,t+1}}{\Pi_{w,t}}-1\right)\frac{\Pi_{w,t+1}}{\Pi_{w,t}}\right)\Gamma_{c,t+1}\frac{\widetilde{W}_{t+1}}{\widetilde{P}_{c,t+1}}L_{t+1}\Bigg] \\
&+\beta^2 E_t\Bigg[\frac{\widetilde{\Lambda}_{c,t+2}}{\widetilde{\Lambda}_{c,t+1}}\frac{\widetilde{\Lambda}_{c,t+1}}{\widetilde{\Lambda}_{c,t}}\left(\Gamma_{c,t+2}\Gamma_{c,t+1}\right)^{-\sigma} \\
&\quad\times\left(\chi_{w,2}\left(\frac{\Pi_{w,t+2}}{\Pi_{w,t+1}}-1\right)\frac{\Pi_{w,t+2}}{\Pi_{w,t+1}}\right)\Gamma_{c,t+2}\Gamma_{c,t+1}\frac{\widetilde{W}_{t+2}}{\widetilde{P}_{c,t+2}}L_{t+2}\Bigg]
\end{aligned} \tag{59}$$

where the stationary marginal utility of consumption $\widetilde{\Lambda}_{c,t}$ is:

$$\widetilde{\Lambda}_{c,t} = \left(\widetilde{C}_t - \eta\frac{\widetilde{C}_{t-1}}{\Gamma_{c,t}}\right)^{-\sigma}\left(\bar{L}-L_t\right)^{\zeta(1-\sigma)} - E_t\beta\eta\left[\Gamma_{c,t+1}^{-\sigma}\left(\widetilde{C}_{t+1} - \eta\frac{\widetilde{C}_t}{\Gamma_{c,t+1}}\right)^{-\sigma}\left(\bar{L}-L_{t+1}\right)^{\zeta(1-\sigma)}\right] \tag{60}$$

while the stationary marginal disutility of labor supply $\widetilde{\Lambda}_{l,t}$ is:

$$\widetilde{\Lambda}_{l,t} = \zeta\left(\widetilde{C}_t - \eta\frac{\widetilde{C}_{t-1}}{\Gamma_{c,t}}\right)^{(1-\sigma)}\left(\bar{L}-L_t\right)^{\zeta(1-\sigma)-1}. \tag{61}$$

The stationary first-order conditions from the second step of intermediate-good producing firm's cost-minimization problem (equations 32 to 35) are

$$\alpha\frac{\left(\widetilde{K}_tU_t\right)^\alpha\left(L_t\right)^{1-\alpha}}{\widetilde{K}_t} = \frac{\widetilde{R}_{k,t}}{\widetilde{MC}_{m,t}} + \Psi\left(U_t\right) \tag{62}$$

$$(1-\alpha)\frac{\left(\widetilde{K}_tU_t\right)^\alpha\left(L_t\right)^{1-\alpha}}{L_t} = \frac{\widetilde{W}_t}{\widetilde{MC}_{m,t}} \tag{63}$$

$$\alpha\frac{\left(\widetilde{K}_tU_t\right)^\alpha\left(L_t\right)^{1-\alpha}}{\widetilde{K}_tU_t} = \Psi'\left(U_t\right) \tag{64}$$

$$\left(\widetilde{K}_tU_t\right)^\alpha\left(L_t\right)^{1-\alpha} = \widetilde{M}_t + \widetilde{K}_t\Psi\left(U_t\right). \tag{65}$$

The stationary Phillips curve from the intermediate-good producing firm's profit-maximization problem :

$$
\begin{aligned}
&\widetilde{MC}_{m,t}\widetilde{Y}_{m,t}\theta \\
&=(\theta-1)(1+\varsigma_\theta)\widetilde{Y}_{m,t}+\left(\chi_{p,1}\left(\Pi_{m,t}-\Pi_m\right)\Pi_{m,t}+\chi_{p,2}\left(\frac{\Pi_{m,t}}{\Pi_{m,t-1}}-1\right)\frac{\Pi_{m,t}}{\Pi_{m,t-1}}\right)\widetilde{Y}_{m,t} \\
&-\beta E_t\left[\frac{\widetilde{\Lambda}_{c,t+1}}{\widetilde{\Lambda}_{c,t}}\frac{\Pi_{m,t+1}}{\Pi_{c,t+1}}\left(\Gamma_{c,t+1}\right)^{-\sigma}\right. \\
&\qquad\left.\times\left(\chi_{p,1}\left(\Pi_{m,t+1}-\Pi_m\right)\Pi_{m,t+1}+2\chi_{p,2}\left(\frac{\Pi_{m,t+1}}{\Pi_{m,t}}-1\right)\frac{\Pi_{m,t+1}}{\Pi_{m,t}}\right)\Gamma_{m,t+1}\widetilde{Y}_{m,t+1}\right] \\
&+\beta^2 E_t\left[\frac{\widetilde{\Lambda}_{c,t+2}}{\widetilde{\Lambda}_{c,t+1}}\frac{\widetilde{\Lambda}_{c,t+1}}{\widetilde{\Lambda}_{c,t}}\frac{\Pi_{m,t+1}}{\Pi_{c,t+1}}\frac{\Pi_{m,t+2}}{\Pi_{c,t+2}}\left(\Gamma_{c,t+2}\Gamma_{c,t+1}\right)^{-\sigma}\right. \\
&\qquad\qquad\left.\times\left(\chi_{p,2}\left(\frac{\Pi_{m,t+2}}{\Pi_{m,t+1}}-1\right)\frac{\Pi_{m,t+2}}{\Pi_{m,t+1}}\right)\Gamma_{m,t+1}\Gamma_{m,t+1}\widetilde{Y}_{m,t+2}\right]. \quad (66)
\end{aligned}
$$

Stationary and Symmetric Steady-state Equilibrium

The steady-state growth rates in the materials, capital, and consumption goods sectors are given by

$$\Gamma_m = \Gamma_{a,m}\Gamma_{a,i}^{\alpha}, \qquad \Gamma_i = \Gamma_{a,m}\Gamma_{a,i}, \qquad \text{and} \qquad \Gamma_c = \Gamma_{a,m}\Gamma_{a,i}^{\alpha}\Gamma_{a,c}^{1-\alpha} \tag{67}$$

where the calibrated values of the growth rates $\Gamma_{a,m}$, $\Gamma_{a,i}$, and $\Gamma_{a,c}$ are given in section 4. The steady-state inflation rates of consumption and capital prices and of nominal wages are given by:

$$\Pi_c = \Pi_m\Gamma_{a,c}^{-(1-\alpha)}, \qquad \Pi_i = \Pi_m\Gamma_{a,i}^{-(1-\alpha)}, \qquad \text{and} \qquad \Pi_w = \Pi_m\Gamma_{a,m}\Gamma_{a,i}^{\alpha}. \tag{68}$$

The nominal interest rate is given by:

$$R = \frac{1}{\beta}\Gamma_c^{\sigma}\Pi_c \tag{69}$$

while the real interest rates relevant to consumers, capitalists, and material good producers respectively are:

$$\frac{R}{\Pi_c} = \frac{1}{\beta}\Gamma_c^{\sigma}, \qquad \frac{R}{\Pi_i} = \frac{1}{\beta}\Gamma_c^{\sigma}\frac{\Pi_c}{\Pi_i}, \qquad \text{and} \qquad \frac{R}{\Pi_m} = \frac{1}{\beta}\Gamma_c^{\sigma}\frac{\Pi_c}{\Pi_m} \tag{70}$$

The steady-state values of the relative prices of consumption, and uninstalled and installed capital goods (that is, $\widetilde{P}_{c,t}$, $\widetilde{P}_{i,t}$, and $\widetilde{Q}_t$) are unity. The steady-state values of real marginal cost, the real rental rate, and the real wage are:

$$\widetilde{MC}_m = \frac{\theta - 1}{\theta}(1 + \zeta_\theta) = 1 \tag{71}$$

$$\widetilde{R}_k = \frac{1}{\beta}\Gamma_c^\sigma \frac{\Pi_c}{\Pi_i} - (1-\delta) = \frac{R}{\Pi_i} - (1-\delta) \tag{72}$$

$$\widetilde{W} = (1-\alpha)\left(\frac{\theta-1}{\theta}\right)^{\frac{1}{1-\alpha}}(1+\zeta_\theta)^{\frac{1}{1-\alpha}}\left(\frac{\alpha}{\frac{R}{\Pi_i} - (1-\delta)}\right)^{\frac{\alpha}{1-\alpha}} \tag{73}$$

The steady-state ratios $\frac{L}{\widetilde{Y}_m}$, $\frac{\widetilde{K}}{\widetilde{Y}_m}$, $\frac{\widetilde{I}}{\widetilde{Y}_m} = \frac{\widetilde{Y}_i}{\widetilde{Y}_m}$, and $\frac{\widetilde{C}}{\widetilde{Y}_m} = \frac{\widetilde{Y}_c}{\widetilde{Y}_m}$:

$$\frac{L}{\widetilde{Y}_m} = \left(\frac{1-\alpha}{\alpha}\right)^\alpha \left(\frac{\widetilde{R}_k}{\widetilde{W}}\right)^\alpha \tag{74}$$

$$\frac{\widetilde{K}}{\widetilde{Y}_m} = \left(\frac{\alpha}{1-\alpha}\right)^{1-\alpha}\left(\frac{\widetilde{W}}{\widetilde{R}_k}\right)^{1-\alpha} \tag{75}$$

$$\frac{\widetilde{I}}{\widetilde{Y}_m} = \frac{\widetilde{Y}_k}{\widetilde{Y}_m} = (\Gamma_i - (1-\delta))\left(\frac{\alpha}{1-\alpha}\right)^{1-\alpha}\left(\frac{\widetilde{W}}{\widetilde{R}_k}\right)^{1-\alpha} \tag{76}$$

$$\frac{\widetilde{C}}{\widetilde{Y}_m} = \frac{\widetilde{Y}_c}{\widetilde{Y}_m} = 1 - (\Gamma_i - (1-\delta))\left(\frac{\alpha}{1-\alpha}\right)^{1-\alpha}\left(\frac{\widetilde{W}}{\widetilde{R}_k}\right)^{1-\alpha} \tag{77}$$

The steady-state solution for materials output is:

$$\widetilde{Y}_m = \bar{L}\left(\frac{L}{\widetilde{Y}_m} + \frac{\zeta}{1 - \eta\Pi_c/R}\cdot\frac{\widetilde{C}}{\widetilde{Y}_m}\cdot\frac{1-\frac{\eta}{\Gamma_c}}{\widetilde{W}}\cdot\frac{\omega}{\omega-1}\cdot\frac{1}{1+\varsigma_\omega}\right)^{-1} \tag{78}$$

Log-Linearized First-order Conditions

The log-linearized versions of the final-good producing firms' first-order conditions are:

$$p_{c,t} = 0 \quad \text{and} \quad p_{k,t} = 0. \tag{79}$$

The demand function from the symmetric equilibrium is

$$y_{m,t} = \frac{\widetilde{Y}_c}{\widetilde{Y}_c + \widetilde{Y}_i} y_{c,t} + \frac{\widetilde{Y}_i}{\widetilde{Y}_c + \widetilde{Y}_i} y_{i,t} \tag{80}$$

where it can be shown that $\frac{\widetilde{Y}_c}{\widetilde{Y}_c + \widetilde{Y}_i}$ and $\frac{\widetilde{Y}_i}{\widetilde{Y}_c + \widetilde{Y}_i}$ are equal to the steady-state nominal shares of consumption and capital goods output in total final goods output respectively. Market clearing in the final goods markets imply that $y_{c,t} = c_t$ and $y_{i,t} = i_t$, together with the equations in (79), allows us to write equation (80) more as a market clearing condition for the materials sector, that is,

$$y_{m,t} = \frac{\widetilde{Y}_c}{\widetilde{Y}_c + \widetilde{Y}_i} c_t + \frac{\widetilde{Y}_i}{\widetilde{Y}_c + \widetilde{Y}_i} i_t \tag{81}$$

The log-linearized versions of the capitalists first-order conditions (55) and (56) are:

$$(i_t + \gamma_{i,t}) + \frac{\Gamma_i \Pi_i}{R} i_t = i_{t-1} + \frac{\Gamma_i \Pi_i}{R} (E_t i_{t+1} + E_t \gamma_{i,t+1}) + \frac{1}{\chi_i \Gamma_i} (q_{k,t} - p_{i,t}) \tag{82}$$

$$E_t r_{k,t+1} - E_t p_{i,t+1} = \frac{R/\Pi_i}{R/\Pi_i - (1-\delta)} (r_t - E_t \pi_{i,t+1} + q_{k,t} - p_{i,t}) - \frac{(1-\delta)}{R/\Pi_i - (1-\delta)} (E_t q_{k,t+1} - E_t p_{i,t+1}) \tag{83}$$

The log-linearized version of the capital evolution equation is:

$$k_t = \left(\frac{1-\delta}{\Gamma_i}\right) k_{t-1} + \left(\frac{\Gamma_i - 1 + \delta}{\Gamma_i}\right) i_{t-1} - \gamma_{i,t} \tag{84}$$

The log-linearized versions of the household's Euler equation (equation 58) and labor supply curve (equation 59) are:

$$\lambda_{c,t} = r_t - E_t \pi_{c,t+1} - \sigma E_t \gamma_{c,t+1} + E_t \lambda_{c,t+1} \tag{85}$$

and

$$\begin{aligned}\left(\chi_{w,1} {\Pi_w}^2 + \chi_{w,2} \left(1 + 2\frac{\Gamma_c \Pi_c}{R}\right)\right) \pi_{w,t} &= \chi_{w,2} \pi_{w,t-1} + \left(\frac{\Gamma_c \Pi_c}{R}\right) \left(\chi_{w,1} {\Pi_w}^2 + \chi_{w,2} \left(2 + \frac{\Gamma_c \Pi_c}{R}\right)\right) E_t \pi_{w,t+1} \\ &\quad - \left(\frac{\Gamma_c \Pi_c}{R}\right)^2 \chi_{w,2} E_t \pi_{w,t+2} + (1 + \varsigma_\omega)(\omega - 1)(\lambda_{l,t} - \lambda_{c,t} - (w_t - p_{c,t}))\end{aligned} \tag{86}$$

where:

$$\begin{aligned}\lambda_{c,t} &= \frac{1}{1 - \eta \Pi_c / R} \left(\frac{-\sigma}{1 - \eta/\Gamma_c} \left(c_t - \frac{\eta}{\Gamma_c} c_{t-1} + \frac{\eta}{\Gamma_c} \gamma_{c,t}\right) - \zeta(1-\sigma) \frac{L}{\bar{L} - L} l_t\right) \\ &\quad - \frac{\eta \Pi_c / R}{1 - \eta \Pi_c / R} \left(\frac{-\sigma}{1 - \eta/\Gamma_c} \left(E_t c_{t+1} - \frac{\eta}{\Gamma_c} c_t + \frac{\eta}{\Gamma_c} E_t \gamma_{c,t+1}\right) - \zeta(1-\sigma) \frac{L}{\bar{L} - L} E_t l_{t+1} - \sigma E_t \gamma_{c,t+1}\right)\end{aligned} \tag{87}$$

and

$$\lambda_{l,t} = \frac{1-\sigma}{1 - \eta/\Gamma_c} \left(c_t - \frac{\eta}{\Gamma_c} c_{t-1} + \frac{\eta}{\Gamma_c} \gamma_{c,t}\right) + (1 - \zeta(1-\sigma)) \left(\frac{L}{\bar{L} - L}\right) l_t. \tag{88}$$

The material producing firms' first-order conditions (equations to 62 to 66) can be log-linearized and rearranged to yield labor and capital demand functions, as well as an equation for the degree of utilization and an expression for marginal cost:

$$l_t = y_{m,t} - \alpha \left(1 + \frac{1-\alpha}{\Psi''(1)/\Psi'(1)}\right) (w_t - r_{k,t}), \tag{89}$$

$$k_t = y_{m,t} + (1-\alpha) \left(1 + \frac{1-\alpha}{\Psi''(1)/\Psi'(1)}\right) (w_t - r_{k,t}), \tag{90}$$

$$u_t = \frac{1-\alpha}{\Psi''(1)/\Psi'(1)} (w_t - r_{k,t}), \tag{91}$$

$$mc_{m,t} = (1-\alpha) w_t + \alpha r_{k,t} \tag{92}$$

and

$$\left(\chi_{p,1}{\Pi_m}^2+\chi_{p,2}\left(1+2\frac{\Gamma_m\Pi_m}{R}\right)\right)\pi_{m,t}=\chi_{p,2}\pi_{m,t-1}+\frac{\Gamma_m\Pi_m}{R}\left(\chi_{p,1}{\Pi_m}^2+\chi_{p,2}\left(2+\frac{\Gamma_m\Pi_m}{R}\right)\right)E_t\pi_{m,t+1}$$
$$-\left(\frac{\Gamma_m\Pi_m}{R}\right)^2\chi_{p,2}E_t\pi_{m,t+2}+(1+\varsigma_\theta)(\theta-1)\,mc_{m,t} \quad (93)$$

The log-linearized first-order conditions for the inflation rates of wages and materials prices imply the following evolution for real wages:

$$E_t w_{t+1}-w_t+E_t\gamma_{a,m,t+1}+E_t\alpha\gamma_{a,i,t+1}=E_t\pi_{w,t+1}-E_t\pi_{m,t+1} \quad (94)$$

while the expected inflation rates for the consumption and capital good prices are given by:

$$E_t\pi_{c,t+1}=E_t\pi_{m,t+1}-(1-\alpha)E_t\gamma_{c,t+1} \quad (95)$$
$$E_t\pi_{i,t+1}=E_t\pi_{m,t+1}-(1-\alpha)E_t\gamma_{i,t+1}. \quad (96)$$

It is worth emphasizing, to avoid confusion, that $\pi_{c,t}$ and $\pi_{i,t}$ represent the change in the *level* of consumption and capital goods prices and *not* the change in the relative prices of consumption and capital goods. Specifically, $\pi_{c,t}\neq p_{c,t}-p_{c,t-1}$ and $\pi_{i,t}\neq p_{i,t}-p_{i,t-1}$. In the flexible wage and price version of our model equations (94), (95), and (96) are given by

$$E_t\pi_{w,t+1}=E_t w_{t+1}-w_t+E_t\gamma_{a,m,t+1}+E_t\alpha\gamma_{a,i,t+1} \quad (97)$$
$$E_t\pi_{c,t+1}=-(1-\alpha)E_t\gamma_{c,t+1} \quad (98)$$
$$E_t\pi_{i,t+1}=-(1-\alpha)E_t\gamma_{i,t+1} \quad (99)$$

Finally, the deviations from steady-state of the growth rates of $A_{c,t}$ and $A_{i,t}$,

$$\gamma_{c,t}=\gamma_{a,m,t}+\alpha\gamma_{a,i,t}+(1-\alpha)\gamma_{a,c,t}$$
$$\gamma_{i,t}=\gamma_{a,m,t}+\gamma_{a,i,t}$$

For almost all variables in the model the title assigned to them it very similar to that variable's empirical concept. One exception is the variable $Q_{k,t}$ in the model, which is the installed price of capital, rather than the ratio of the price of installed to uninstalled capital. For this we introduce a variable Q_t^{tobin} defined at $\frac{Q_{k,t}}{P_{i,t}}$ so that in our log-linearized equations it is the term $q_{k,t}-p_{i,t}=q_t^{tobin}$ that is the log-deviation of Tobin's q from its steady-state value of unity.

Estimation Appendix

In this appendix, we reproduce the VAR specification and identification section from Edge, Laubach, and Williams (2003).

VAR Specification and Identification

The specification of our VAR and the assumptions for identifying structural shocks are in most respects the same as those of Altig, Christiano, Eichenbaum, and Linde (2002), and the reader is referred to that paper. Nine variables are included in the VAR: the first difference of log labor productivity, inflation, log manufacturing capacity utilization, the log labor share, log hours per person, the log nominal consumption-to-output ratio, the log nominal investment-to-output ratio, the nominal funds rate, and (linearly detrended) log M2 velocity. Labor productivity, the labor share, and hours are the BLS measures for the nonfarm business sector, where the labor share is computed as output per hour times the deflator for nonfarm business output divided by compensation per hour.[13] Inflation is computed using the GDP deflator. Population is the civilian population age 16 and over. The consumption-to-output ratio is computed as the share of nominal personal consumption of nondurables and services plus nominal government consumption expenditures in nominal GDP. Similarly, the investment-to-output ratio is computed as the share of nominal personal durable goods expenditures plus gross nominal private investment plus nominal government investment expenditures in nominal GDP.[14]

Letting Y_t denote the vector of variables in the VAR, and v_t log M2 velocity, we view the data in the VAR as corresponding, up to constants, to the model variables

$$Y_t = [\Delta(y_{m,t} - l_t), \pi_{m,t}, u_t, y_{m,t} - l_t - w_t, l_t, c_t + p_{c,t} - y_{m,t}, i_t + p_{i,t} - y_{m,t}, r_t, v_t]',$$

where lower case letters denote logs of the model variables. We estimate the VAR over the

[13] By contrast, Altig *et al.* (2002) and Galí, López-Salido, and Vallés (2003) compute labor productivity by dividing real GDP by total hours in the nonfarm business sector, which is problematic because of the trending share of real nonfarm business output in real GDP.

[14] We compute these ratios as shares of GDP, instead of as shares of nonfarm business output because some consumption of goods and services are not produced by the nonfarm business sector. However, this introduces a minor inconsistency in the VAR impulse responses of output, consumption, and investment presented in Figures 1 and 2. The latter two are constructed by adding the responses of the respective log ratios to the response of nonfarm business output.

sample 1960q1 to 2001q4, including four lags of each variable.

Following a number of other recent studies, we are interested in identifying two structural shocks, a permanent shock to the level of technology (in terms of our model, in the intermediate goods sector), and a transitory shock to the funds rate. To identify these shocks, we use one long-run and two short-run identifying restrictions. The short-run identifying restrictions are the usual ones, that the second-to-last and the last variable in the VAR (the funds rate and velocity) are Wold-causal for the preceding variables. Writing the structural form of the VAR as

$$A_0 Y_t = \mathit{constant} + A(L)Y_{t-1} + \varepsilon_t, \tag{100}$$

the short-run assumptions imply that the last two columns of the contemporaneous multiplier matrix A_0 have all zeros above the main diagonal. The eighth element of ε_t is identified as the funds rate shock. The long-run identifying restriction is the one proposed by Galí (1999) and further explored in Francis and Ramey (2002) and Altig *et al.* (2002), that permanent shocks to technology are the only shocks to have a permanent effect on labor productivity. Using this assumption, we identify the first element of ε_t as the technology shock.[15] This implies that the first row of the matrix of long-run (cumulative) effects of ε_t on Y_t, $(I - A(1))^{-1}A_0^{-1}$, consists of zeros except for the first element.

In order to estimate the VAR in structural form, we need a further set of assumptions to just-identify the elements of A_0. We follow Altig *et al.* (2002) in assuming that the submatrix consisting of columns 2-7 and rows 2-7 of A_0 is lower triangular. This assumption is without loss of generality as we do not attach any structural interpretation to elements 2 through 7 of ε_t. With these assumptions, we estimate the first equation of the structural VAR imposing the long-run restrictions in the manner of Shapiro and Watson (1988) by including contemporaneous and lagged variables of elements 2 through 7 of Y_t in first-differenced form. To control for simultaneity, we estimate the equation by 2SLS, using a constant and $Y_{t-1}, \ldots, Y_{t-4}$ as first-stage regressors for elements 2 through 7 of Y_t. We then sequentially estimate equations 2 through 7 by IV, using the residuals from the previous regressions as instruments for contemporaneous variables. Equations 8 and 9 can be estimated by OLS by virtue of our short-run identifying assumptions.

[15] Other shocks, including those to investment goods sector productivity and the tax rate on capital income, can affect the level labor productivity in the long run. See, for example, Fisher (2002).

Given the VAR impulse responses to our identified technology shock and identified funds rate shock (Figures 1 and 2), we estimated the parameters of the model that influence the model's dynamic (rather than steady-state) properties. Our method of estimation was to minimize the squared deviations of the response of eight variables $(y_{m,t}, c_t, i_t, l_t, u_t, w_t, \pi_{m,t}, r_t)$ to the two identified shocks implies by the model and from those implied by the VAR. For the technology shock we use the responses in quarters 0 through 20 following the shock; for the funds rate shock, we use the responses in quarters 1 trhough 20, since the responses in the quarter of the shock are determined by the identifying assumption. (The impulse responses for the eight variables following the two identified shocks, received equal weights in our estimation.)