TECHNOLOGY SHOCKS IN A TWO-SECTOR DSGE MODEL

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ABSTRACT. Recent evidence suggests that output, consumption, investment and hours rise in response to improvements in the technology for producing consumption goods, but all decline on impact when there is a similar improvement in investment-goods technology. We show that these effects are consistent with the predictions of a dynamic stochastic general equilibrium (DSGE) model with two sectors—a consumption good sector and an investment good sector—with sticky prices in each sector. The assumption that investment goods prices are also costly to adjust differentiates our model from previous research in this area, and helps us fit the evidence that the relative price of investment goods adjusts slowly to shocks. In combination with recent empirical work, our paper suggests that sector-specific technology shocks may be a major source of US business cycle dynamics, and models that were developed to fit the estimated effects of monetary policy shocks can also explain the estimated effects of sector-specific technology shocks.

I. INTRODUCTION

What shocks drive business cycles? At a minimum, such shocks must move output, consumption, investment and hours worked in the same direction, as this positive comovement is a defining characteristic of business cycles. Technology shocks are attractive candidates, because they can reproduce this comovement in simple, general-equilibrium models of fluctuations. But in the data, technology shocks identified using restrictions from one-sector models do not produce positive comovement. In particular, Galí (1999) and Basu, Fernald, and Kimball (2006) find that an aggregate technology improvement often raises output and consumption, but lowers hours worked. Reviewing this evidence, Francies and Ramey (2005) conclude "the original technology-driven business cycle hypothesis does appear to be dead."

In this paper, we reconsider whether technology shocks can match business-cycle facts in the context of a two-sector sticky-price DSGE model. Our focus on such a model is

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motivated by empirical evidence from Basu, Fernald, Fisher, and Kimball (2011) (BFFK) and Fisher (2006) that the economy's response differs depending on the final-expenditure category that the shock affects. For example, BFFK find that shocks to the ability to produce either investment goods or consumption goods has appropriate business-cycle comovement properties. Strikingly, investment technology improvements are contractionary, whereas consumption-technology improvements are expansionary. Aggregating the two shocks into a single measure of technical change is a specification error, since the two have dramatically different dynamic effects. It also leads to the mistaken impression that technology shocks do not induce business cycle comovements. The results in Fisher (2006) and, especially, in BFFK (2011) suggest that it is time to resuscitate the technology-driven business cycle model.[1]

The data suggest that consumption- and investment-specific technology shocks both induce positive comovement among the four key macro aggregates, but do so in very different ways. In this paper, we explore whether the patterns of comovement found in the recent empirical literature are consistent with a fairly standard, two-sector DSGE model with nominal wage and price stickiness. We use this class of models because the profession has concluded that it does well at explaining the estimated effects of monetary policy shocks (Christiano, Eichenbaum, and Evans, 2005; Smets and Wouters, 2007; Liu, Waggoner, and Zha, 2011).

However, relative to the existing literature, we make a significant change: We allow both consumption and investment goods to be sold with sticky prices. The existing literature, following Smets and Wouters (2007), has allowed for two independent technology shocks, but assumed that the price of investment goods is fully flexible while the price of consumption goods is sticky. It is not appealing to assume a priori that one category of prices behaves so differently from another. Allowing symmetric price stickiness shows that a technology improvement of the same size can have very different economic effects depending on the sector that it affects. Strikingly, these differential effects are quite consistent with the estimated findings of BFFK (2011).

Our model has an investment sector and a consumption sector. Both sectors have sticky prices but different technology processes. Sticky prices are necessary even to explain the estimated effects of technology shocks because the flex-price model fails to fit the evidence of slow pass-through of technology shocks to relative prices. Many New Keynesian DSGE models, such as Smets and Wouters (2007), include an investment-specific shock that can be interpreted as a shock to the relative price of investment goods. But for this shock to correspond to a relative technology shock, the relative price of investment and consumption goods must be perfectly flexible. With sector- (or firm-)

[1]However, we do not propose to "resuscitate real business cycles," as King and Rebelo (1999) put it. We find that it is critical to allow for non-neoclassical propagation mechanisms in order to match the estimated effects of technology shocks in the data.

specific sticky prices, in contrast, relative prices adjust only slowly to shocks. We find that our two-sector model can reproduce the empirical evidence that investment technology improvements are contractionary, whereas consumption technology improvements are expansionary. In our model, the two shocks cause movements in key business cycle variables with appropriate comovement properties.

Economically, the relative-price rigidity plays a central role in explaining the effects of sector-specific technology shocks. The predominant effects of both shocks work through the markup of price over marginal cost in the *investment* sector. With a sticky investment price, an improvement to investment technology causes the markup to rise relative to the steady state in the investment sector. In other words, investment goods are relatively expensive today relative to future periods. Since the intertemporal elasticity of substitution is very high for investment goods, current demand for investment goods falls. An improvement in consumption technology, in contrast, causes wages and, therefore, the marginal cost of production of the investment good to rise. This squeezes the investment markup-and spurs investment purchases. Since output in the short run is largely demand-determined in this model, output and hours worked generally follow demand for investment goods.

We begin by discussing some stylized facts from the empirical literature. We then write down a two-sector DSGE model, and discuss what properties of the model can explain the facts.

II. Stylized Facts

Empirical evidence from two separate identification schemes finds that the economy responds differently to technology shocks that affect the ability to produce investment goods versus consumption goods. The first scheme, using results from Basu, Fernald, Fisher, and Kimball (2011), is based on estimating industry technology residuals and mapping through the input-output matrix to final uses. The second scheme uses long-run restrictions, and involves a rearrangement of Fisher (2006) results.

Table 1 shows results from regressing variables on final-use technology shocks from BFFK. The industry technology residuals control for factor utilization and non-constant returns to scale. The shocks are then fed through the input-output table to match to final expenditure categories.

The table shows that improvements in investment technology are sharply contractionary: investment, consumption, hours worked, and output all decline temporarily, and rise only with a lag. In contrast, improvements in consumption technology have little effect on hours but are expansionary on impact for both consumption and investment. Note that both consumption technology and investment technology improvements look like business cycles: hours, consumption, investment, and output all comove together.

The table also shows that the relative price of investment does not respond rapidly to either technology shock, though the response is more notable for the consumption technology shock. BFFK (2011) show that relative technology does pass through to relative prices. But the pass-through takes at least 3 years to complete.

A very different identification scheme comes from Fisher (2006). Fisher identifies two shocks using long-run restrictions. One shock, the "investment-specific" shock, is the only one allowed to affect the long-run relative price of investment goods. That shock, plus a second "neutral" shock, are the only ones that affect the long-run level of labor productivity.

The shocks identified by Fisher (2006) can be mapped to final use sectors. It is straightforward to show that the investment-sector shock corresponds to the investment-specific shock. A "consumption" shock requires a positive neutral shock, but also an offsetting negative investment-specific shock (to keep the overall effect on investment unchanged). Thus, the consumption shock corresponds to the difference between the neutral and investment-specific shocks. With the Fisher identification, we do not have the response for the full set of variables.

Figure 1 shows that, prior to 1979, the Fisher identification finds that investment shocks are contractionary while consumption shocks are expansionary for labor hours. These results are consistent with the BFFK results. One caveat is that Fisher finds that his estimates differ before and after 1979. In the later sample, the investment shock is expansionary whereas the consumption shock is contractionary. In contrast, BFFK find subsample results that are consistent with those we already discussed in Table 1–investment shocks are contractionary whereas consumption shocks are expansionary throughout the sample.

Figure 2 shows that, with the Fisher identification, it takes a long time for the technology shocks to pass through to the relative price. The response of the relative price to investment shocks is particularly slow. This pattern holds for both sub-sample periods and is consistent with the finding of slow pass-through in BFFK (2011). The macro effects of the technology shocks on hours are apparent long before the relative price effects show up.

III. The Model

The model economy is populated by a continuum of households, each endowed with a unit of differentiated labor skill. There are two goods-producing sectors, a consumption sector and an investment sector. Firms in each sector produce differentiated products. The monetary authority follows a feedback interest rate rule.

III.1. **The aggregation sector.** The aggregation sector produces a composite labor skill denoted by L_t, a composite final consumption good denoted by Y_{ct}, and a composite investment good denoted by Y_{it}. Production of the composite skill requires a continuum of differentiated labor skills $\{L_t(h)\}_{h\in[0,1]}$ as inputs. Production of the composite consumption (investment) good requires a continuum of differentiated intermediate goods $\{Y_{ct}(n)\}_{n\in[0,1]}$ ($\{Y_{it}(n)\}_{n\in[0,1]}$) as inputs. The aggregation technologies are given by

$$L_t = \left[\int_0^1 L_t(h)^{\frac{1}{\mu_{wt}}} dh\right]^{\mu_{wt}}, \quad Y_{ct} = \left[\int_0^1 Y_{ct}(n)^{\frac{1}{\mu_{ct}}} dj\right]^{\mu_{ct}}, \quad Y_{it} = \left[\int_0^1 Y_{it}(n)^{\frac{1}{\mu_{it}}} dz\right]^{\mu_{it}}, \tag{1}$$

where μ_{wt}, μ_{ct}, and μ_{it} determine the elasticities of substitution between differentiated skills and differentiated intermediate goods in the two sectors, respectively. Following Smets and Wouters (2007), we assume that

$$\ln \mu_{wt} = (1-\rho_{\mu w}) \ln \mu_w + \rho_{\mu w} \ln \mu_{w,t-1} + \sigma_{\mu w} (\varepsilon_{\mu w,t} - \phi_{\mu w}\varepsilon_{\mu w,t-1}), \tag{2}$$

$$\ln \mu_{ct} = (1-\rho_{\mu c}) \ln \mu_c + \rho_{\mu c} \ln \mu_{c,t-1} + \sigma_{\mu c} (\varepsilon_{\mu c,t} - \phi_{\mu c}\varepsilon_{\mu c,t-1}), \tag{3}$$

$$\ln \mu_{it} = (1-\rho_{\mu i}) \ln \mu_i + \rho_{\mu i} \ln \mu_{i,t-1} + \sigma_{\mu i} (\varepsilon_{\mu i,t} - \phi_{\mu i}\varepsilon_{\mu i,t-1}), \tag{4}$$

where, for $k \in \{\mu w, \mu c, \mu i\}$, $\rho_k \in (-1, 1)$ is the AR(1) coefficient, ϕ_k is the MA(1) coefficient, σ_k is the standard deviation, and ε_{kt} is an i.i.d. standard normal process. We interpret μ_{wt} as the wage markup shock and μ_{ct} and μ_{it} as the price markup shocks in the two sectors. The difference in markup across the consumption sector and the investment sector allows for reallocation effects that potentially amplify technology shocks (Basu and Fernald, 1997).

The representative firm in the aggregation sector faces perfectly competitive markets. The demand functions for differentiated labor skills and intermediate goods are given by

$$L_t^d(h) = \left[\frac{W_t(h)}{\bar{W}_t}\right]^{-\frac{\mu_{wt}}{\mu_{wt}-1}} L_t, \quad Y_{ct}^d(n) = \left[\frac{P_{ct}(n)}{\bar{P}_{ct}}\right]^{-\frac{\mu_{ct}}{\mu_{ct}-1}} Y_{ct}, \quad Y_{it}^d(n) = \left[\frac{P_{it}(n)}{\bar{P}_{it}}\right]^{-\frac{\mu_{it}}{\mu_{it}-1}} Y_{it}, \tag{5}$$

where the wage rate $\bar{W}_t$ of the composite skill is related to the individual wage rates by $\bar{W}_t = \left[\int_0^1 W_t(h)^{1/(1-\mu_{wt})} dh\right]^{1-\mu_{wt}}$, the price indexes $\bar{P}_{ct}$ and $\bar{P}_{it}$ for consumption and investment goods are related to individual prices by $\bar{P}_{ct} = \left[\int_0^1 P_{ct}(n)^{1/(1-\mu_{ct})} dn\right]^{1-\mu_{ct}}$ and $\bar{P}_{it} = \left[\int_0^1 P_{it}(n)^{1/(1-\mu_{it})} dn\right]^{1-\mu_{it}}$.

III.2. **The intermediate good sectors.** We now describe the production technologies and price-setting decisions of intermediate goods producers in the consumption sector and the investment sector. We focus on describing the consumption sector. The description for the investment sector is symmetric.

III.2.1. *The consumption sector.* Production of a type n intermediate good in the consumption sector (i.e., the C-sector) requires labor and capital inputs. The production functions are given by

$$Y_{ct}(n) = Z_{ct} K_{ct}(n)^{\alpha_c} [\gamma_c^t L_{ct}(n)]^{1-\alpha_c} - \lambda_t^* \Phi_c, \tag{6}$$

where $K_{ct}(n)$ and $L_{ct}(n)$ are the capital and labor inputs and λ_t^* denotes the underlying trend for C-sector output. The parameter α_c denotes the cost share the capital, γ^c denotes the trend growth rate of the technology, and Φ_c is a fixed cost in the C-sector. The term Z_{ct} denotes a technology shock in the C-sector, which follows the stochastic process

$$\ln Z_{ct} = (1 - \rho_{zc})) \ln Z_c + \rho_{zc} \ln Z_{c,t-1} + \sigma_{zc}\varepsilon_{ct}, \tag{7}$$

where $\rho_{zc} \in (-1, 1)$ measures the persistence, σ_{zc} denotes the standard deviation, and ε_{ct} is an i.i.d. standard normal process.

Firms in the intermediate-good sector are price takers in the input markets and monopolistic competitors in the product markets. A firm $n \in [0, 1]$ in the consumption goods sector chooses labor and capital input to minimize the cost $\bar{W}_t L_{ct}(n) + \bar{P}_{it} r_{kt} K_{ct}(n)$ subject to the production technology (6), taking as given the nominal wage index $\bar{W}_t$ and the nominal capital rental rate $\bar{P}_{it} r_{kt}$, where r_{kt} is the real capital rental rate in investment goods unit. The conditional factor demand functions derived from the cost-minimizing problem imply that

$$\frac{w_t}{q_{it} r_{kt}} = \frac{1 - \alpha_c}{\alpha_c} \frac{K_{ct}(n)}{L_{ct}(n)}, \quad \forall n \in [0, 1], \tag{8}$$

where $w_t \equiv \frac{\bar{W}_t}{\bar{P}_{ct}}$ denotes the real consumption wage and $q_{it} = \frac{\bar{P}_{it}}{\bar{P}_{ct}}$ denotes the relative price of investment goods.

Each firm sets a price for its own differentiated product, taking as given the demand schedule in (5). We follow Calvo (1983) and assume that pricing decisions are staggered across firms within each sector. Once a price is set, the firm has no other choice but to supply its differentiated product to meet market demand at that price. Denote by ξ_c the probability that a firm in the consumption sector cannot re-optimize price setting.

Following Woodford (2003), Christiano, Eichenbaum, and Evans (2005), and Smets and Wouters (2007), we allow a fraction of firms that cannot re-optimize to index their prices to the consumption sector's overall price inflation realized in the past period. Specifically, if the firm n in the consumption sector cannot set a new price, its price is automatically updated according to

$$P_{ct}(n) = \pi_{c,t-1}^{\eta_c} \pi_c^{1-\eta_c} P_{c,t-1}(n), \tag{9}$$

where $\pi_{ct} \equiv \frac{\bar{P}_{ct}}{\bar{P}_{c,t-1}}$ is the consumption price inflation rate between $t - 1$ and t, π_c is steady-state consumption inflation, and η_c measures the degree of dynamic indexation.

A firm that can renew its price contract chooses $P_{ct}(n)$ to maximize its expected discounted dividend flows given by

$$\mathrm{E}_t \sum_{s=0}^{\infty} \xi_c^s D_{t,t+s} [P_{ct}(n) \chi_{t,t+s}^c Y_{c,t+s}^d(n) - V_{c,t+s}(n)], \tag{10}$$

where $D_{t,t+s}$ is the period-t present value of a dollar in a future state in period $t + s$, $V_{c,t+s}(n)$ is the total cost function, and the term $\chi_{t,t+s}^c$ is a cumulative inflation-indexation factor given by

$$\chi^c_{t,t+s} = \begin{cases} \Pi_{k=1}^s \pi_{c,t+k-1}^{\eta_c} \pi_c^{1-\eta_c} & \text{if } s \geq 1 \\ 1 & \text{if } s = 0. \end{cases} \tag{11}$$

In maximizing its profit, the firm takes as given the demand schedule

$$Y^d_{c,t+s}(n) = \left(\frac{P_{ct}(n)\chi^c_{t,t+s}}{\bar{P}_{c,t+s}} \right)^{-\frac{\mu_{c,t+s}}{\mu_{c,t+s}-1}} Y_{c,t+s}.$$

Profit-maximizing implies the optimal pricing rule

$$\mathrm{E}_t \sum_{s=0}^{\infty} \xi_c^s D_{t,t+s} Y^d_{c,t+s}(n) \frac{1}{\mu_{c,t+s}-1} \left[\mu_{c,t+s} \bar{P}_{c,t+s} v_{c,t+s} - P_{ct}(n) \chi^c_{t,t+s} \right] = 0, \tag{12}$$

where $v_{c,t+s}$ denotes the real marginal cost function (in consumption units) given by

$$v_{ct} = \frac{\tilde{\alpha}_c}{Z_{ct}} \left(q_{it} r_{kt} \right)^{\alpha_c} \left(\frac{w_t}{\gamma_c^t} \right)^{1-\alpha_c}, \tag{13}$$

where $\tilde{\alpha}_c \equiv \alpha_c^{-\alpha_c} (1-\alpha_c)^{\alpha_c - 1}$.

If there is no markup shock, then (12) implies that the optimal price is a markup over an average of the marginal costs for the periods during which the price remains effective. Clearly, if $\xi_c = 0$, that is, if prices are perfectly flexible, then the optimal price would be a markup over the contemporaneous marginal cost.

III.2.2. *The investment sector.* Similar to the consumption sector, the production technology for a type n investment good is given by

$$Y_{it}(n) = Z_{it} K_{it}(n)^{\alpha_i} [\gamma_i^t L_{it}(n)]^{1-\alpha_i} - \gamma_i^t \Phi_i, \tag{14}$$

where $K_{it}(n)$ and $L_{it}(n)$ are the capital and labor inputs, Z_{it} is an investment-specific technology shock, γ_i denotes the trend growth rate of investment technology, and Φ_i denotes a fixed cost. The investment technology shock Z_{it} follows a stochastic process symmetric to the consumption technology shock described in (7), with a slight change in notation.

The nature of nominal rigidities in the investment sector is also symmetric to that in the consumption sector. Briefly, there is a fraction ξ_i of firms cannot re-optimize pricing decisions in each period. The prices that cannot be re-optimized are automatically indexed to past inflation in the investment sector. A firm that can adjust its price chooses a price to maximize the present value of profit, taking the demand schedule for its product as given. The optimal pricing decision rule is given by

$$\mathrm{E}_t \sum_{s=0}^{\infty} \xi_i^s D_{t,t+s} Y^d_{i,t+s}(n) \frac{1}{\mu_{i,t+s}-1} \left[\mu_{i,t+s} \bar{P}_{c,t+s} v_{i,t+s} - P_{it}(n) \chi^I_{t,t+s} \right] = 0, \tag{15}$$

where the real marginal cost v_{it} (in consumption units) is given by

$$v_{it} = \frac{\tilde{\alpha}_i}{Z_{it}} \left(q_{it} r_{kt} \right)^{\alpha_i} \left(\frac{w_t}{\gamma_i^t} \right)^{1-\alpha_i}, \tag{16}$$

and the term $\chi^I_{t,t+i}$ summarizes the cumulative inflation indexation factor and is given by

$$\chi^I_{t,t+s} = \begin{cases} \Pi^s_{k=1} \pi^{\eta_i}_{i,t+k-1} \pi_i^{1-\eta_i} & \text{if } s \geq 1 \\ 1 & \text{if } s = 0, \end{cases} \tag{17}$$

with π_{it} denoting changes in the price level of the investment sector (i.e., investment price inflation).

Cost-minimizing implies that the conditional factor demand functions in the investment sector are given by

$$\frac{w_t}{q_{it} r_{kt}} = \frac{1-\alpha_i}{\alpha_i} \frac{K_{it}(n)}{L_{it}(n)}, \quad \forall n \in [0,1]. \tag{18}$$

III.3. **The households.** There is a continuum of households, each endowed with a differentiated labor skill indexed by $h \in [0,1]$. Household h derives utility from consumption and leisure. We follow Blanchard and Kiyotaki (1987) and assume that each household is a price-taker in the goods market and a monopolistic competitor in the labor market, where she sets a nominal wage for her differentiated labor skill, taking as given the wage index and the downward-sloping labor demand schedule in (5). The nominal wage-setting decisions by households are staggered in the spirit of Calvo (1983). Once a nominal wage rate is set, the household has to supply labor to meet the market demand for her differentiated skill at that wage rate (so quitting her job is not an option). We assume that there exists financial instruments that provide perfect insurance for the households in different wage-setting cohorts, so that the households make identical consumption and investment decisions despite that their wage incomes may differ due to staggered wage setting.[2] In what follows, we impose this assumption and omit the household index for consumption and investment.

The utility function for household $h \in [0,1]$ is given by

$$\mathrm{E} \sum_{t=0}^{\infty} \beta^t A_t U(C_t - bC_{t-1}, L_t(h)), \tag{19}$$

where $\beta \in (0,1)$ is a subjective discount factor, C_t denotes consumption, $L_t(h)$ denotes hours worked, and b measures the importance of habit formation. The variable A_t is a shock to the discount factor. Denote by $\lambda_{at} = \frac{A_t}{A_{t-1}}$. We assume that λ_{at} follows the stationary process

$$\ln \lambda_{at} = \rho_a \ln \lambda_{a,t-1} + \sigma_a \varepsilon_{at}, \tag{20}$$

[2]To obtain complete risk-sharing among households in different wage-setting cohorts does not rely on the existence of such (implicit) financial arrangements. As shown by Huang, Liu, and Phaneuf (2004) and Smets and Wouters (2007), the same equilibrium dynamics can be obtained in a model with a representative household (and thus complete insurance) consisting of a large number of worker members. The workers supply their homogenous labor skill to a large number of employment agencies, who transform the homogenous skill into differentiated skills and set nominal wages in a staggered fashion.

where $\rho_a \in (-1, 1)$ is the persistence parameter, σ_a is the standard deviation, and ε_{at} is an i.i.d. standard normal process.

In each period t, the household faces the budget constraint

$$\bar{P}_{ct}C_t + \bar{P}_{it}[I_t + a(u_t)K_{t-1}] + \mathrm{E}_t D_{t,t+1}B_{t+1} \leq \\ W_t(h)L_t^d(h) + \bar{P}_{it}r_{kt}u_t K_{t-1} + \Pi_t + B_t - T_t. \tag{21}$$

In the budget constraint, I_t denotes investment; B_{t+1} is a nominal state-contingent bond that represents a claim to one dollar in a particular event in period $t+1$, and this claim costs $D_{t,t+1}$ dollars in period t; $W_t(h)$ is the nominal wage for h's labor skill, K_{t-1} is the beginning-of-period capital stock, u_t is the utilization rate of capital, Π_t is the profit share, and T_t is a lump-sum taxes used by the government to finance exogenous government spending. The term $a(u_t)$ denotes the cost of variable capital utilization. Following Christiano, Eichenbaum, and Evans (2005) and Altig, Christiano, Eichenbaum, and Linde (forthcoming), we assume that $a(u)$ is increasing and convex and that, at the steady-state utilization rate of $u = 1$, we have $a(1) = 0$.

The capital stock evolves according to the law of motion

$$K_t = (1-\delta)K_{t-1} + \chi_t \left[1 - S\left(\frac{I_t}{K_{t-1}}\right)\right] I_t, \tag{22}$$

where the function $S(\cdot)$ represents the adjustment cost in capital accumulation. We assume that $S(\cdot)$ is convex and satisfies $S(\tilde{I}\gamma_i/\tilde{K}) = S'(\tilde{I}\gamma_i/\tilde{K}) = 0$, where $\tilde{I}/\tilde{K}$ is the steady-state ratio of investment to capital stock. The term χ_t is a shock to the marginal efficiency of transforming investment goods into capital goods (or "MEI"), a shock emphasized by Justiniano, Primiceri, and Tambalotti (2011). The MEI shock follows the stationary stochastic process

$$\ln \chi_t = \rho_\chi \ln \chi_{t-1} + \sigma_\chi \varepsilon_{\chi t}, \tag{23}$$

where $\rho_\chi \in (-1, 1)$ is the persistence parameter, σ_χ is the standard deviation, and $\varepsilon_{\chi t}$ is an i.i.d. standard normal process.

The household takes prices and all wages but its own as given and chooses C_t, I_t, K_t, u_t, B_{t+1}, and $W_t(h)$ to maximize (19) subject to (21) - (22), the borrowing constraint $B_{t+1} \geq -\underline{B}$ for some large positive number $\underline{B}$, and the labor demand schedule $L_t^d(h)$ described in (5).

Denote by μ_t and μ_{kt} the Lagrangian multipliers for (21) and (22), respectively. The first order conditions for the utility-maximizing problem are given by

$$A_t U_{ct} = \mu_t \bar{P}_{ct}, \tag{24}$$

$$D_{t,t+1} = \beta \frac{\mu_{t+1}}{\mu_t}, \tag{25}$$

$$\mu_t \bar{P}_{it} = \mu_{kt}\chi_t \left[1 - S\left(\frac{I_t}{K_{t-1}}\right) - S'\left(\frac{I_t}{K_{t-1}}\right)\frac{I_t}{K_{t-1}}\right], \tag{26}$$

$$\mu_{kt} = \beta \mathrm{E}_t \left\{ \mu_{k,t+1}\left[1 - \delta + \chi_{t+1} S'\left(\frac{I_{t+1}}{K_t}\right)\left(\frac{I_{t+1}}{K_t}\right)^2\right] + \mu_{t+1}\bar{P}_{i,t+1}[r_{k,t+1}u_{t+1} - a(u_{t+1})] \right\}, \tag{27}$$

$$r_{kt} = a'(u_t), \tag{28}$$

where $\lambda_{It} \equiv I_t/I_{t-1}$ denotes the growth rate of investment, $q_{it} \equiv \frac{\bar{P}_{it}}{\bar{P}_{ct}}$ denotes the relative price of aggregate investment goods, and $r_{kt} = \frac{R_{kt}}{\bar{P}_{ct}}$ denotes the real rental rate of capital in consumption units.

Denote by $q_{kt} \equiv \frac{\mu_{kt}}{\mu_t \bar{P}_{ct}}$ the shadow price of capital stock in consumption units. Then, (24) and (26) imply that

$$q_{it} = q_{kt}\chi_t \left[1 - S\left(\frac{I_t}{K_{t-1}}\right) - S'\left(\frac{I_t}{K_{t-1}}\right)\frac{I_t}{K_{t-1}}\right]. \tag{29}$$

By eliminating the Lagrangian multipliers μ_t and μ_{kt}, the capital Euler equation (27) can be rewritten as

$$q_{kt} = \beta \mathrm{E}_t \frac{A_{t+1}U_{c,t+1}}{A_t U_{ct}} \left\{ q_{k,t+1}\left[1 - \delta + \chi_{t+1} S'\left(\frac{I_{t+1}}{K_t}\right)\left(\frac{I_{t+1}}{K_t}\right)^2\right] + q_{i,t+1}[r_{k,t+1}u_{t+1} - a(u_{t+1})] \right\}. \tag{30}$$

The cost of acquiring a marginal unit of capital is q_{kt} today (in consumption unit). The benefit of having this extra unit of capital consists of the expected discounted future resale value and the rental value net of utilization cost.

By eliminating the Lagrangian multiplier μ_t, the first-order condition with respect to bond holding can be written as

$$D_{t,t+1} = \beta \frac{A_{t+1}U_{c,t+1}}{A_t U_{ct}} \frac{\bar{P}_{ct}}{\bar{P}_{c,t+1}}. \tag{31}$$

Denote by $R_t = [\mathrm{E}_t D_{t,t+1}]^{-1}$ the interest rate for a one-period risk-free nominal bond. Then we have

$$\frac{1}{R_t} = \beta \mathrm{E}_t \left[\frac{A_{t+1}U_{c,t+1}}{A_t U_{ct}} \frac{\bar{P}_{ct}}{\bar{P}_{c,t+1}}\right]. \tag{32}$$

The wage-setting decisions are staggered across households. In each period, a fraction ξ_w of households cannot re-optimize their wage decisions and, among those who cannot re-optimize, a fraction γ_w of them index their nominal wages to the price inflation realized in the past period. In particular, if the household h cannot set a new nominal wage, its wage is automatically updated according to

$$W_t(h) = \pi_{c,t-1}^{\eta_w} \pi_c^{1-\eta_w} \lambda_{t-1,t}^* W_{t-1}(h), \tag{33}$$

where $\lambda_{t-1,t}^*$ denotes the trend growth rate of aggregate output (and of real wage). If a household $h \in [0,1]$ can re-optimize its nominal wage-setting decision, it chooses $W(h)$ to maximize the utility subject to the budget constraint (21) and the labor demand schedule in (5). The optimal wage-setting decision implies that

$$\mathrm{E}_t \sum_{s=0}^{\infty} \xi_w^s D_{t,t+s} L_{t+s}^d(h) \frac{1}{\mu_{w,t+s} - 1} [\mu_{w,t+s} \bar{P}_{c,t+s} MRS_{t+s}(h) - W_t(h) \chi_{t,t+s}^w] = 0, \tag{34}$$

where $MRS_t(h) = -U_{lt}/U_{ct}$ denotes the marginal rate of substitution between leisure and income for household h and $\chi_{t,t+s}^w$ is a cumulative wage indexation factor defined as

$$\chi_{t,t+s}^w \equiv \begin{cases} \Pi_{k=1}^s \pi_{c,t+k-1}^{\eta_w} \pi_c^{1-\eta_w} \lambda_{t+k-1,t+k}^* & \text{if } s \geq 1 \\ 1 & \text{if } s = 0. \end{cases} \tag{35}$$

In the absence of wage-markup shocks, μ_{wt} would be a constant and (34) implies that the optimal wage is a constant markup over a weighted average of the marginal rate of substitution for the periods in which the nominal wage remains effective. If $\xi_w = 0$, then the nominal wage adjustments are flexible and (34) implies that the nominal wage is a markup over the contemporaneous marginal rate of substitution.

III.4. **The government and monetary policy.** The government follows Ricardian fiscal policy, with its spending financed by lump-sum taxes so that $\bar{P}_{ct} G_t = T_t$, where G_t denotes the government spending in final consumption units. Denote by $\tilde{G}_t \equiv \frac{G_t}{\lambda_t^*}$ the detrended government spending, where

$$\lambda_t^* \equiv (\gamma_c^t)^{1-\alpha_c} (\gamma_i^t)^{\alpha_c}. \tag{36}$$

We follow Smets and Wouters (2007) and assume that the government spending shock is persistent and responds to C-sector productivity shocks. In particular, $\tilde{G}_t$ follows the stationary stochastic process

$$\ln \tilde{G}_t = (1-\rho_g) \ln \tilde{G} + \rho_g \ln \tilde{G}_{t-1} + \sigma_g \varepsilon_{gt} + \rho_{gz} \sigma_{zc} \varepsilon_{ct}. \tag{37}$$

Monetary policy is characterized by a Taylor rule, under which the nominal interest rate is set to respond to deviations of consumer price inflation from a target and changes in detrended real GDP. Consistent with the National Income and Product Accounts (NIPA), we define real GDP as an expenditure-share weighted average of consumption, investment, and government spending. In particular, we have

$$Y_t = C_t^{s_c} I_t^{s_i} G_t^{s_g}, \tag{38}$$

where s_c, s_i, and s_g are the NIPA expenditure shares.

The monetary policy rule is given by

$$R_t = r\pi_c \left(\frac{\pi_{ct}}{\pi_c}\right)^{\phi_\pi} \left(\frac{\tilde{Y}_t}{\tilde{Y}}\right)^{\phi_y} e^{\sigma_r \varepsilon_{rt}}, \tag{39}$$

where $R_t = [\mathrm{E}_t D_{t,t+1}]^{-1}$ denotes the nominal interest rate, $\tilde{Y}_t$ denotes detrended real GDP, and r denotes the steady-state real interest rate.

In the interest rate rule (39), the constant terms ϕ_π, and ϕ_y are policy parameters. The term ε_{rt} denotes a monetary policy shock, which follows an i.i.d. standard normal process. The term σ_r is the standard deviation of the monetary policy shock.[3]

III.5. **Market clearing and equilibrium.** In equilibrium, markets for bond, composite labor, capital stock, and final goods all clear. Bond market clearing implies that $B_t = 0$ for all t. Labor market clearing implies that

$$\int_0^1 L_{ct}(z)dz + \int_0^1 L_{it}(n)dn = L_t. \tag{40}$$

Capital market clearing implies that

$$\int_0^1 K_{ct}(z)dz + \int_0^1 K_{it}(n)dn = u_t K_{t-1}. \tag{41}$$

Goods market clearing in the two sectors implies that

$$C_t + G_t = Y_{ct}, \quad I_t + a(u_t)K_{t-1} = Y_{it}, \tag{42}$$

where Y_{ct} and Y_{it} are aggregate outputs in the two sectors.

Aggregate output in each sector is related to primary factors through the aggregate production functions

$$G_{ct}Y_{ct} = Z_{ct}K_{ct}^{\alpha_c}(\gamma_c^t L_{ct})^{1-\alpha_c} - \lambda_t^* \Phi_c, \tag{43}$$

$$G_{it}Y_{it} = Z_{it}K_{it}^{\alpha_i}(\gamma_i^t L_{it})^{1-\alpha_i} - \gamma_i^t \Phi_i, \tag{44}$$

where $G_{jt} \equiv \int_0^1 \left(\frac{P_{jt}(n)}{P_{jt}}\right)^{-\frac{\mu_{jt}}{\mu_{jt}-1}} dn$ measures the price dispersion for sector $j \in \{c, i\}$ and L_{jt} and K_{jt} denote aggregate labor and capital inputs in sector j.

Given fiscal and monetary policy, an *equilibrium* in this economy consists of prices and allocations such that (i) taking prices and all nominal wages but its own as given, each household's allocation and nominal wage solve its utility maximization problem; (ii) taking wages and all prices but its own as given, each firm's allocation and price in each sector solve its profit maximization problem; (iii) markets for bond, composite labor, capital stock, and final goods all clear.

[3] Under the interest rate rule (39), monetary policy is targeting consumption price inflation but not directly investment price inflation. One can easily modify the rule specification to study monetary policy that targets a weighted average of the inflation rates in the two sectors (i.e., some version of GDP deflator targeting).

IV. Equilibrium Dynamics

IV.1. **Stationary equilibrium and the deterministic steady state.** We focus on a stationary equilibrium with balanced growth. On a balanced growth path, output, consumption, investment, capital stock, and the real wage all grow at constant rates, while hours remain constant. Further, in the presence of investment-specific technological change, investment and capital grow at a faster rate.

To obtain balanced growth, we generalize the King-Plosser-Rebelo utility function to incorporate habit persistence and consider the utility functional form

$$U(C_t - bC_{t-1}, L_t) = \frac{(C_t - bC_{t-1})^{1-\sigma}}{1-\sigma} e^{(\sigma-1)V(L_t)}, \tag{45}$$

where $\sigma > 0$ is the inverse intertemporal elasticity of substitution (when labor is held constant) and $V(L_t)$ is the utility of leisure. A version of this utility function without habit persistence appears in Basu and Kimball (2002).

With this utility function, the marginal utility of consumption is given by

$$U_{ct} = (C_t - bC_{t-1})^{-\sigma} e^{(\sigma-1)V(L_t)} - \beta b \mathrm{E_t} \frac{\mathrm{A_{t+1}}}{\mathrm{A_t}} (\mathrm{C_{t+1}} - \mathrm{bC_t})^{-\sigma} \mathrm{e}^{(\sigma-1)\mathrm{V(L_{t+1})}}, \tag{46}$$

and the marginal dis-utility of working is given by

$$-U_{lt} = (C_t - bC_{t-1})^{1-\sigma} e^{(\sigma-1)V(L_t)} V'(L_t). \tag{47}$$

To induce stationarity, we transform variables so that

$$\tilde{Y}_{ct} = \frac{Y_{ct}}{\lambda_t^*}, \quad \tilde{Y}_{it} = \frac{Y_{it}}{\gamma_i^t}, \quad \tilde{Y}_t = \frac{Y_t}{\lambda_{yt}}, \quad \tilde{C}_t = \frac{C_t}{\lambda_t^*}, \quad \tilde{I}_t = \frac{I_t}{\gamma_i^t}, \quad \tilde{K}_t = \frac{K_t}{\gamma_i^t}, \quad \tilde{K}_{ct} = \frac{K_{ct}}{\gamma_i^t},$$

$$\tilde{K}_{it} = \frac{K_{it}}{\gamma_i^t}, \quad \tilde{w}_t = \frac{W_t}{\bar{P}_t \lambda_t^*}, \quad \tilde{q}_{it} = \frac{q_{it}\gamma_i^t}{\lambda_t^*}, \quad \tilde{q}_{kt} = \frac{q_{kt}\gamma_i^t}{\lambda_t^*}, \quad \tilde{U}_{ct} = U_{ct}\lambda_t^{*\sigma}, \quad \tilde{U}_{lt} = U_{lt}\lambda_t^{*\sigma-1},$$

where λ_t^* is the underlying trend for consumption-sector output, consumption, and the real wage given by (36) and λ_{yt} is the underlying trend for real GDP given by

$$\lambda_{yt} = [\lambda^{s_c+s_g}\gamma_i^{s_i}]^t, \tag{48}$$

where $\lambda = \gamma_c^{1-\alpha_c}\gamma_i^{\alpha_c}$ denotes the growth rate of consumption sector output.

A deterministic steady state in the model is the stationary equilibrium in which all shocks are shut off. In the steady state, investment grows at the rate $\lambda_I = \gamma_i$ and consumption and government spending grow at the rate λ. We assume that $u = 1$, $a(1) = 0$, and $S(\lambda_I) = S'(\lambda_I) = 0$. The steady-state conditions are summarized in the Appendix A.

IV.2. **Linearized equilibrium dynamics.** To solve for the equilibrium dynamics, we log-linearize the equilibrium conditions around the deterministic steady state. We use a hatted variable $\hat{x}_t$ to denote the log-deviations of the stationary variable X_t from its steady-state value (i.e., $\hat{x}_t = \ln(X_t/X)$).

Linearizing the optimal pricing decision rule for the consumption sector implies that

$$\hat{\pi}_{ct} - \eta_c \hat{\pi}_{c,t-1} = \kappa_c(\hat{\mu}_{ct} + \hat{v}_{ct}) + \beta\lambda^{1-\sigma}\mathrm{E}_t[\hat{\pi}_{c,t+1} - \eta_c \hat{\pi}_{ct}], \tag{49}$$

where $\kappa_c \equiv \frac{(1-\beta\lambda^{1-\sigma}\xi_c)(1-\xi_c)}{\xi_c}$ and the real marginal cost is given by

$$\hat{v}_{ct} = [\alpha_c(\hat{q}_{it} + \hat{r}_{kt}) + (1-\alpha_c)\hat{w}_t - \hat{z}_{ct}]. \tag{50}$$

This is the standard price Phillips-curve relation generalized to allow for partial dynamic indexation. In the special case without indexation (i.e., $\eta_c = 0$), this relation reduces to the standard forward-looking Phillips curve relation, under which the price inflation depends on the current-period real marginal cost and the expected future inflation. In the presence of dynamic indexation, the price inflation also depends on its own lag.

Similarly, log-linearizing the optimal pricing decision rule for the investment sector leads to the Phillips curve for the I-sector

$$\hat{\pi}_{it} - \eta_i \hat{\pi}_{i,t-1} = \kappa_i(\hat{\mu}_{it} + \hat{v}_{it} - \hat{q}_{it}) + \beta\lambda^{1-\sigma}\mathrm{E}_t[\hat{\pi}_{i,t+1} - \eta_i \hat{\pi}_{it}], \tag{51}$$

where $\kappa_i \equiv \frac{(1-\beta\lambda^{1-\sigma}\xi_i)(1-\xi_i)}{\xi_i}$ and the real marginal cost (in consumption units) is given by

$$\hat{v}_{it} = [\alpha_i(\hat{q}_{it} + \hat{r}_{kt}) + (1-\alpha_i)\hat{w}_t - \hat{z}_{it}]. \tag{52}$$

Note that, since the real marginal cost $\hat{v}_{it}$ is in consumption units, the effective real marginal cost (in investment units) for an investment-sector firm is given by $\hat{v}_{it} - \hat{q}_{it}$.

Linearizing the optimal wage-setting decision rule implies that

$$\hat{w}_t - \hat{w}_{t-1} + \hat{\pi}_{ct} - \eta_w \hat{\pi}_{c,t-1} = \frac{\kappa_w}{1+\eta\theta_w}(\hat{\mu}_{wt} + m\hat{r}s_t - \hat{w}_t) + \beta\lambda^{1-\sigma}\mathrm{E}_t[\hat{w}_{t+1} - \hat{w}_t + \hat{\pi}_{c,t+1} - \eta_w \hat{\pi}_{ct}], \tag{53}$$

where $\hat{w}_t$ denotes the log-deviations of the real wage, $m\hat{r}s_t = -\hat{U}_{lt} - \hat{U}_{ct}$ denotes the marginal rate of substitution between leisure and consumption, $\theta_w \equiv \frac{\mu_w}{\mu_w - 1}$, and $\kappa_w \equiv \frac{(1-\beta\lambda^{1-\sigma}\xi_w)(1-\xi_w)}{\xi_w}$ is a constant. To help understand the economics of this equation, we rewrite this relation in terms of the nominal wage inflation:

$$\hat{\pi}^w_t - \eta_w \hat{\pi}_{c,t-1} = \frac{\kappa_w}{1+\eta\theta_w}(\hat{\mu}_{wt} + m\hat{r}s_t - \hat{w}_t) + \beta\lambda^{1-\sigma}\mathrm{E}_t(\hat{\pi}^w_{t+1} - \eta_w \hat{\pi}_{ct}).$$

where $\hat{\pi}^w_t = \hat{w}_t - \hat{w}_{t-1} + \hat{\pi}_{ct}$ denotes the nominal wage inflation. This nominal-wage Phillips curve relation parallels that of the price-Phillips curves and has similar interpretations.

The rest of the linearized equilibrium conditions are fairly standard and we put them in the appendix.

V. Calibration

To evaluate the quantitative implications of our model, we solve the model's equilibrium dynamics based on calibrated parameters. We calibrate the model parameters to fit several first-moment observations in the postwar U.S. data. Tables 2 and 3 summarizes our calibration. To help exposition, we put the parameters in 5 different groups.

The first group of parameters are those in production and capital accumulation technologies. These include the cost share of capital in the C-sector α_c and in the I-sector α_i; the growth rate of labor-augmenting technology in the two sectors γ_c and γ_i; the average markup for wage-setting μ_w and for price setting in the two sectors μ_c and μ_i; the capital depreciation rate δ; the local curvature of the utilization function $\sigma_u = \frac{a''(1)}{a'(1)}$; and the curvature of the capital adjustment cost function $S''(\lambda_I)$. We set $\gamma_c = 1.0043$ and $\gamma_i = 1.01$ based on the estimates obtained by Liu, Waggoner, and Zha (2011). We set $\alpha_c = 0.33$ and $\alpha_i = 0.33$, so that the labor share in each sector is about 2/3. The implied real per capita consumption growth rate is about $\lambda = \gamma_i^{\alpha}\gamma_c^{1-\alpha} = 1.006$, or 2.4 percent per year, which is close to the data. Following Huang and Liu (2002) and Christiano, Eichenbaum, and Evans (2005), we set the elasticity of substitution between differentiated labor skills to $\theta_w = 6$, implying a steady-state wage markup of $\mu_w = 1.2$. We set the elasticity of substitution between differentiated goods in the C-sector and the I-sector to $\theta_c = 10$ and $\theta_i = 10$, implying that the steady-state price markups are $\mu_c = 1.11$ and $\mu_i = 1.11$, which are in line with micro studies (Basu and Fernald, 1997).

We calibrate δ so that the steady-state investment-to-capital ratio is about 0.166 per annual, which matches the average ratio of the annual flow of investment in equipment and software plus consumer durable expenditures to the stock of capital in the same category for the period from 1960 to 2010. In particular, the steady-state capital law of motion implies that

$$\frac{I}{K} = 1 - \frac{1-\delta}{\gamma_i}.$$

This relation implies that $\delta = 0.033$ per quarter. Based on the estimation by Liu, Waggoner, and Zha (2011), we set $\sigma_u = 2.26$. We set $S''\left(\frac{\gamma_i \tilde{I}}{\tilde{K}}\right) = 5.0$, which is in the range of existing estimates.

The second group of parameters are those in the utility function. We assume that the disutility of labor takes the functional form $V(L) = \psi \frac{L^{1+\eta}}{1+\eta}$. The preference parameters include the subjective discount factor β, the habit persistence parameter b, the inverse intertemporal elasticity of substitution σ, the inverse Frisch elasticity of labor η, and the utility weight on leisure ψ. We set $\beta = 0.9962$, which implies a steady-state real interest rate of $\lambda/\beta = 1.01$, or 4 percent per annual. We follow Boldrin, Christiano, and Fisher (2001) and set $b = 0.70$. We set $\sigma = 3$, corresponding to an intertemporal elasticity of substitution of 1/3, which is close to the estimates obtained in micro studies (Vissing-Jorgensen, 2002). We set $\eta = 0.5$, corresponding to a Frisch elasticity of labor supply of 2, which is in line with the macro labor literature (Keane and Rogerson, 2011). Finally, we adjust ψ so that the steady-state working time is about 1/3 of total time endowment (i.e., $L = 1/3$).

The third group of parameters are those related to nominal rigidities. These include the Calvo price-adjustment parameters ξ_c for the C-sector, ξ_i for the I-sector, and ξ_w for wage-setting households; and the dynamic indexation parameters η_c, η_i, and η_w. As a benchmark, we set $\xi_c = 0.75$, $\xi_i = 0.75$, and $\xi_w = 0.75$ so that price and wage contracts last on average for 4 quarters. Based on the estimates by Smets and Wouters (2007), we set $\eta_c = 0.22$, $\eta_i = 0.22$, and $\eta_w = 0.59$.

The fourth group of parameters are those in the monetary policy rule, including ϕ_π and ϕ_y. We set $\phi_\pi = 1.50$, and $\phi_y = 0.10$ as a benchmark.

The fifth and final group of parameters are those in the shock processes, including the persistence parameters, the moving average parameters, and the standard deviations. We focus on the dynamic effects of technology shocks in the two sectors. We calibrate the sector-specific technology shock processes from the quarterly investment- and consumption-sector series on utilization-adjusted total factor productivity constructed by Fernald (2012). Since measures of TFP growth are defined in first-differences, we first convert the growth rates into levels (by cumulative sums). The levels of technology shocks in both sectors contain time-varying trends, with at least one significant trend break according to a Bai-Perron test in each sector. We estimate an AR(1) with two breaks in a linear time trend for each technology shock series. For investment, the breaks represent a speedup in trend in 1994:Q4 and a slowdown in trend in 2005:Q4; for consumption, the breaks show a slowdown in 1968:Q3 and a further slowdown in 2003:Q4. In both cases, allowing for the first break substantially reduces the autocorrelation coefficient, but the second break only modestly reduces it.

The estimates from these AR(1) regressions imply an autocorrelation of 0.85 for the consumption sector technology shock and 0.94 for the investment sector technology shock. The standard deviations of the regression residuals are 0.838 and 1.00 for the consumption sector and the investment sector, respectively. Thus, we set $\rho_{zc} = 0.85, \rho_{zi} = 0.94, \sigma_{zc} = 0.838$ and $\sigma_{zi} = 1.00$.

VI. Economic implications

We solve the model based on the calibrated parameters. We examine the model's transmission mechanisms based on impulse responses, focusing on the effects of the consumption-goods sector technology shock and the investment-goods sector technology shock. The big-picture issue is whether or not the model can generate the observed comovements of macroeconomic variables following each type of technology shocks. In particular, empirical studies by Basu, Fernald, Fisher, and Kimball (2011) show that a C-sector technology improvement leads to an expansion of all macro variables whereas an I-sector technology improvement leads to a short-run contraction. Further, the pass-through from the I-sector technology shock to the relative price of investment goods is gradual (Fisher, 2006; Basu, Fernald, Fisher, and Kimball, 2011). The standard one-sector model cannot generate these observed comovements and slow pass-through. Can the two-sector DSGE model here do better than the one-sector model? If so, what mechanisms are essential?

Figure 3 plots the impulse responses of several macroeconomic variables following a positive shock to the consumption sector technology in both the benchmark model with sticky prices in both the C-sector and the I-sector (solid lines) and in an alternative model with sticky consumption prices but flexible investment prices. The figure shows that, in both models, a technology improvement in the consumption sector generates a business cycle boom, in which real GDP, consumption, investment, and employment all rise persistently. The shock leads to a fall in consumption price inflation and a rise in the relative price of investment. Comparing the impulse responses across the two models reveals that having sticky prices in the investment sector helps amplify the consumption technology shock, but the qualitative patterns of the macroeconomic responses to technology improvement in the C-sector do not depend on whether investment goods prices are sticky.

Sticky investment prices do affect the macroeconomic responses to technology improvement in the I-sector. Figure 4 plots the impulse responses of the same set of macro variables following a positive shock to the investment sector technology. In the benchmark model with sticky prices in both sectors (solid lines), the I-sector shock generates a short-run recession—in contrast to the expansionary effects of the C-sector shock. Real GDP, consumption, investment, and employment all decline in the short run, then overshoot the steady-state levels, before returning to the steady-state levels in the long run. The shock generates a persistent, U-shaped decline in the relative price of investment goods. Although the decline in the relative price creates an incentive for increases in investment spending, the expectation of further declines in the relative price more than offsets the initial substitution effect and agents choose to postpone investment to "cash in" future sales. The decline in investment spending lowers aggregate demand for labor and capital, reduces short-run income for the households, and thus leads to a short-run decline in consumption as well. Over time, however, as the investment-goods prices adjust gradually to catch up with the declined marginal cost in that sector, the relative price stops declining and investment starts to take place. This leads to a medium-term expansion following the transitory technology improvement in the investment-goods sector. These results are broadly consistent with empirical findings in the literature based on sectoral level data, most notably the study by Basu, Fernald, Fisher, and Kimball (2011).

When investment goods prices are flexible, however, the patterns of macroeconomic responses to the I-sector technology improvement are different from the benchmark model. As shown in Figure 4, with flexible I-sector prices, the I-sector technology shock would be expansionary (dashed lines). Real GDP, consumption, investment, and employment all rise following the I-sector shock. The relative price of investment goods falls sharply on impact of the shock, creating incentive for increases in investment spending, and thus raising aggregate demand. The expansionary effects of the I-sector technology improvement predicted by the model with flexible investment prices (and sticky consumption prices) are counterfactual. Thus, have sticky prices in both sectors is important for understanding the macroeconomic effects of technology shocks.

VII. Conclusion

Recent empirical studies suggest that a consumption-sector technology improvement typically leads to a business-cycle expansion, whereas an investment-sector technology improvement leads to a short-run contraction. We show that these effects are consistent with the predictions of a dynamic stochastic general equilibrium (DSGE) model with two sectors—a consumption good sector and an investment good sector—with sticky prices in each sector. The assumption that investment goods prices are also costly to adjust differentiates our model from previous research in this area, and helps us fit the evidence that the relative price of investment goods adjusts slowly to shocks. In combination with recent empirical work, our paper suggests that sector-specific technology shocks may be a major source of US business cycle dynamics, and models that were developed to fit the estimated effects of monetary policy shocks can also explain the estimated effects of sector-specific technology shocks.

Appendix A. Steady state

A deterministic steady state in the model is the stationary equilibrium in which all shocks are shut off. In the steady state, investment grows at the rate $\lambda_I = \gamma_i$ and consumption and government spending grow at the rate λ. We assume that $u = 1$, $a(1) = 0$, and $S(\lambda_I) = S'(\lambda_I) = 0$. Further, in the steady state, the classical dichotomy obtains so that we can solve out the real allocations and relative prices independently of monetary policy. We then determine the nominal variables based on the real variables and monetary policy. The real variables in the steady state are determined by the following equations:

$$1 = \mu_c v_c, \tag{A1}$$

$$\tilde{q}_i = \mu_i v_i, \tag{A2}$$

$$v_c = \frac{\tilde{\alpha}_c}{Z_c} (\tilde{q}_i r_k)^{\alpha_c} \tilde{w}^{1-\alpha_c}, \tag{A3}$$

$$v_i = \frac{\tilde{\alpha}_i}{Z_i} (\tilde{q}_i r_k)^{\alpha_i} \tilde{w}^{1-\alpha_i}, \tag{A4}$$

$$\frac{\tilde{w}}{\tilde{q}_i r_k} = \frac{1-\alpha_c}{\alpha_c} \frac{\tilde{K}_c}{L_c}, \tag{A5}$$

$$\frac{\tilde{w}}{\tilde{q}_i r_k} = \frac{1-\alpha_i}{\alpha_i} \frac{\tilde{K}_i}{L_i}, \tag{A6}$$

$$\mu_c \tilde{Y}_c = Z_c \tilde{K}_c^{\alpha_c} L_c^{1-\alpha_c}, \tag{A7}$$

$$\mu_i \tilde{Y}_i = Z_i \tilde{K}_i^{\alpha_i} L_i^{1-\alpha_i}, \tag{A8}$$

$$L = L_c + L_i, \tag{A9}$$

$$\frac{\tilde{K}}{\gamma_i} = \tilde{K}_c + \tilde{K}_i, \tag{A10}$$

$$\tilde{Y}_c = \tilde{C} + \tilde{G}, \tag{A11}$$

$$\tilde{Y}_i = \tilde{I}, \tag{A12}$$

$$\frac{\tilde{I}}{\tilde{K}} = 1 - \frac{1-\delta}{\gamma_i}, \tag{A13}$$

$$r_k = \frac{\gamma_i}{\beta \lambda^{1-\sigma}} - (1-\delta), \tag{A14}$$

$$\tilde{w} = \mu_w \frac{\lambda - b}{\lambda - \beta \lambda^{1-\sigma} b} \tilde{C} V'(L). \tag{A15}$$

The first 2 equations (A1) and (A2) are the steady-state optimal pricing decisions for firms in the C-sector and the I-sector. The next 2 equations (A3) and (A4) are the steady-state real marginal costs in the two sectors. Equations (A5) and (A6) are the optimal factor demand equations in the two sectors. Equations (A7) and (A8) are the aggregate production functions in the two sectors. Equations (A9) and (A10) are the market clearing conditions for labor and capital. Equations (A11) and (A12) are the market clearing conditions for C-sector goods and I-sector goods. Equation (A13) is derived from the capital law of motion for the steady state. Equation (A14) gives the marginal product of capital in the steady-state derived from the capital Euler equation. Finally, (A15) is the steady-state optimal wage-setting equation. These 15 equations determine the steady-state values of the 15 endogenous real variables

$$[v_c,\ v_i,\ \tilde{q}_i,\ r_k,\ \tilde{w},\ \tilde{K}_c,\ \tilde{K}_i,\ L_c,\ L_i,\ \tilde{Y}_c,\ \tilde{Y}_i,\ L,\ K,\ I,\ C]'.$$

We go through the following steps to obtain closed-form solutions for these 15 variables.

First, we solve $r_k, v_c, v_i, \tilde{q}_i$, and $\tilde{w}$ using equations (A1)-(A4) and (A14). The solutions are given by

$$v_c = \frac{1}{\mu_c}, \tag{A16}$$

$$r_k = \frac{\gamma_i}{\beta\lambda^{1-\sigma}} - (1-\delta), \tag{A17}$$

$$\tilde{w} = v_c \frac{Z_c}{\tilde{\alpha}_c}\left[\mu_i \frac{\tilde{\alpha}_i}{Z_i} r_k\right]^{-\frac{\alpha_c}{1-\alpha_i}}, \tag{A18}$$

$$\tilde{q}_i = \left[\mu_i \frac{\tilde{\alpha}_i}{Z_i} r_k^{\alpha_i}\right]^{\frac{1}{1-\alpha_i}} \tilde{w} = \left[\mu_i \frac{\tilde{\alpha}_i}{Z_i}\right]^{\frac{1-\alpha_c}{1-\alpha_i}} r_k^{\frac{\alpha_i-\alpha_c}{1-\alpha_i}} \frac{Z_c}{\mu_c \tilde{\alpha}_c}, \tag{A19}$$

$$v_i = \frac{\tilde{q}_i}{\mu_i}. \tag{A20}$$

Note that, if the two sectors have identical factor shares and markups, then (A19) implies that the steady-state relative price of I-goods would be the same as the inverse of the relative productivity, which is the case studied by Greenwood, Hercowitz, and Krusell (1997) and Fisher (2006).

Second, given the solutions for $\tilde{w}$, $\tilde{q}_i$, and r_k, we have the solutions for $\frac{\tilde{K}_c}{L_c}$ and $\frac{\tilde{K}_i}{L_i}$ from (A5) and (A6).

Third, we use the solution for $\frac{\tilde{K}_i}{L_i}$ and the I-goods market clearing condition (A12) to rewrite the aggregate production function (A8) for I-goods as

$$\frac{\tilde{I}}{\tilde{K}} = \frac{Z_i}{\mu_i}\left(\frac{\tilde{K}_i}{L_i}\right)^{\alpha_i - 1}\frac{\tilde{K}_i}{\tilde{K}},$$

Using (A13) to substitute out $\frac{\tilde{I}}{\tilde{K}}$, we obtain

$$\frac{\tilde{K}_i}{\tilde{K}} = \frac{\mu_i}{Z_i}\left(\frac{\tilde{K}_i}{L_i}\right)^{1-\alpha_i}\left(1 - \frac{1-\delta}{\gamma_i}\right). \tag{A21}$$

We then use the capital market clearing condition (A10) to obtain

$$\frac{\tilde{K}_c}{\tilde{K}} = \frac{1}{\gamma_i} - \frac{\tilde{K}_i}{\tilde{K}}. \tag{A22}$$

Fourth, we divide (A5) by (A6) to obtain

$$\frac{L_c}{L_i} = \frac{(1-\alpha_c)\alpha_i}{(1-\alpha_i)\alpha_c}\frac{\tilde{K}_c/\tilde{K}}{\tilde{K}_i/\tilde{K}}. \tag{A23}$$

This solution, along with the labor market clearing condition (A9), implies the solutions for $\frac{L_c}{L}$ and $\frac{L_i}{L}$.

Fifth, we divide through the C-sector production function (A7) by L to obtain

$$\mu_c \frac{\tilde{Y}_c}{L} = Z_c \left(\frac{\tilde{K}_c}{L_c}\right)^{\alpha_c}\frac{L_c}{L},$$

which gives the solution for $\frac{\tilde{Y}_c}{L}$. Using the C-goods market clearing condition, we obtain

$$\frac{\tilde{C}}{L} = \frac{\tilde{Y}_c}{L}(1-g),$$

where $g \equiv \frac{\tilde{G}}{\tilde{Y}_c}$ denotes the steady-state ratio of government spending to C-sector output, which is assumed to be exogenous. To solve for L, we use (A15) to obtain

$$V'(L)L = \frac{\tilde{w}}{\mu_w}\frac{\lambda - \beta\lambda^{1-\sigma}b}{\lambda - b}\left(\frac{\tilde{C}}{L}\right)^{-1}. \tag{A24}$$

Once we obtain solutions for the 15 real variables above, it is straightforward to derive the solutions for the remaining 8 endogenous steady-state variables for a given R (determined by monetary policy). These are given by

$$\pi_c = \frac{\beta}{\lambda^\sigma}R, \tag{A25}$$

$$\pi_i = \pi_c, \tag{A26}$$

$$u = 1, \tag{A27}$$

$$\tilde{q}_k = \tilde{q}_i, \tag{A28}$$

$$\tilde{Y} = \tilde{C}^{s_c}\tilde{I}^{s_i}\tilde{G}^{s_g}, \tag{A29}$$

$$\tilde{U}_c = \frac{\lambda^\sigma - \beta b}{\left[\tilde{C}(\lambda - b)\right]^\sigma}e^{(\sigma-1)V(L)}, \tag{A30}$$

$$-\tilde{U}_l = \left[\tilde{C}\left(\frac{\lambda - b}{\lambda}\right)\right]^{1-\sigma} e^{(\sigma-1)V(L)}V'(L), \tag{A31}$$

$$MRS = \frac{-\tilde{U}_l}{\tilde{U}_c} = \frac{\lambda - b}{\lambda - \beta\lambda^{1-\sigma}b}\tilde{C}V'(L). \tag{A32}$$

Equation (A25) is the steady-state inflation rate in the C-sector derived from the bond Euler equation. Equation (A26) gives the I-sector inflation, which equals the C-sector inflation since the relative price of I-goods is constant in the steady state. Equation (A27) is the steady-state capacity utilization rate, which is normalized to one. Equation (A28) is the steady-state Tobin's q, which equals the relative price of investment goods. Equation (A29) is the definition of real GDP. Equations (A27)-(A32) are the steady-state marginal utilities of consumption and leisure and the MRS. This completes our derivation of the steady-state equilibrium.

Appendix B. Log-linearized equilibrium conditions

We now summarize the full set of log-linearized equilibrium conditions.

$$\hat{\pi}_{ct} - \eta_c\hat{\pi}_{c,t-1} = \kappa_c(\hat{\mu}_{ct} + \hat{v}_{ct}) + \beta\lambda^{1-\sigma}\mathrm{E}_t[\hat{\pi}_{c,t+1} - \eta_c\hat{\pi}_{ct}], \tag{A33}$$

$$\hat{\pi}_{it} - \eta_i\hat{\pi}_{i,t-1} = \kappa_i(\hat{\mu}_{it} + \hat{v}_{it} - \hat{q}_{it}) + \beta\lambda^{1-\sigma}\mathrm{E}_t[\hat{\pi}_{i,t+1} - \eta_i\hat{\pi}_{it}], \tag{A34}$$

$$\hat{w}_t - \hat{w}_{t-1} + \hat{\pi}_{ct} - \eta_w\hat{\pi}_{c,t-1} = \frac{\kappa_w}{1+\eta\theta_w}(\hat{\mu}_{wt} + m\hat{r}s_t - \hat{w}_t) + \beta\lambda^{1-\sigma}\mathrm{E}_t[\hat{w}_{t+1} - \hat{w}_t + \hat{\pi}_{c,t+1} - \eta_w\hat{\pi}_{ct}], \tag{A35}$$

$$\hat{v}_{ct} = [\alpha_c(\hat{q}_{it} + \hat{r}_{kt}) + (1-\alpha_c)\hat{w}_t - \hat{z}_{ct}]. \tag{A36}$$

$$\hat{v}_{it} = [\alpha_i(\hat{q}_{it} + \hat{r}_{kt}) + (1-\alpha_i)\hat{w}_t - \hat{z}_{it}]. \tag{A37}$$

$$\hat{q}_{it} = \hat{q}_{i,t-1} + \hat{\pi}_{it} - \hat{\pi}_{ct}, \tag{A38}$$

$$\hat{q}_{kt} = \hat{q}_{it} - \hat{\chi}_t + S''\left(\frac{\tilde{I}\gamma_i}{\tilde{K}}\right)\left(\frac{\tilde{I}\gamma_i}{\tilde{K}}\right)^2(\hat{i}_t - \hat{k}_{t-1}), \tag{A39}$$

$$\hat{q}_{kt} = \mathrm{E}_t\left\{\Delta\hat{a}_{t+1} + \Delta\hat{U}_{c,t+1} + \frac{\beta\lambda^{1-\sigma}}{\gamma_i}\left[(1-\delta)\hat{q}_{k,t+1} + r_k(\hat{q}_{i,t+1} + \hat{r}_{k,t+1})\right]\right\} + \frac{\beta\lambda^{1-\sigma}}{\gamma_i}S''\left(\frac{\tilde{I}\gamma_i}{\tilde{K}}\right)\left(\frac{\tilde{I}\gamma_i}{\tilde{K}}\right)^3\mathrm{E_t}(\hat{\mathrm{i}}_{\mathrm{t+1}} - \hat{\mathrm{k}}_{\mathrm{t}}), \tag{A40}$$

$$\hat{r}_{kt} = \sigma_u\hat{u}_t, \tag{A41}$$

$$0 = \mathrm{E}_t\left[\Delta\hat{a}_{t+1} + \Delta\hat{U}_{c,t+1} + \hat{R}_t - \hat{\pi}_{c,t+1}\right], \tag{A42}$$

$$\hat{k}_t = \frac{1-\delta}{\gamma_i}\hat{k}_{t-1} + \left(1 - \frac{1-\delta}{\gamma_i}\right)(\hat{\chi}_t + \hat{i}_t), \tag{A43}$$

$$\hat{y}_{ct} = c_y\hat{c}_t + (1-c_y)\hat{g}_t, \tag{A44}$$

$$\hat{y}_{it} = \hat{i}_t + s_u\hat{u}_t, \tag{A45}$$

$$\hat{l}_t = \frac{L_c}{L}\hat{l}_{ct} + \frac{L_i}{L}\hat{l}_{it}, \tag{A46}$$

$$\hat{u}_t + \hat{k}_{t-1} = \frac{\gamma_i K_c}{K}\hat{k}_{ct} + \frac{\gamma_i K_i}{K}\hat{k}_{it}, \tag{A47}$$

$$\hat{w}_t = \hat{q}_{it} + \hat{r}_{kt} + \hat{k}_{ct} - \hat{l}_{ct}, \tag{A48}$$

$$\hat{w}_t = \hat{q}_{it} + \hat{r}_{kt} + \hat{k}_{it} - \hat{l}_{it}, \tag{A49}$$

$$\hat{y}_{ct} = \mu_c\left[\hat{z}_{ct} + \alpha_c\hat{k}_{ct} + (1-\alpha_c)\hat{l}_{ct}\right], \tag{A50}$$

$$\hat{y}_{it} = \mu_i\left[\hat{z}_{it} + \alpha_i\hat{k}_{it} + (1-\alpha_i)\hat{l}_{it}\right], \tag{A51}$$

$$\hat{y}_t = s_c\hat{c}_t + s_i\hat{i}_t + s_g\hat{g}_t, \tag{A52}$$

$$\hat{R}_t = \rho_r\hat{R}_{t-1} + (1-\rho_r)\left[\phi_\pi\hat{\pi}_{ct} + \phi_y\hat{y}_t\right] + \sigma_r\varepsilon_{rt}, \tag{A53}$$

$$\hat{U}_{ct} = -\frac{\sigma\lambda^\sigma}{(\lambda^\sigma - \beta b)(\lambda - b)}(\lambda\hat{c}_t - b\hat{c}_{t-1}) + \frac{\sigma\beta b}{(\lambda^\sigma - \beta b)(\lambda - b)}(\lambda\mathrm{E_t}\hat{\mathrm{c}}_{\mathrm{t+1}} - \mathrm{b}\hat{\mathrm{c}}_{\mathrm{t}}) + \frac{\beta b}{\lambda^\sigma - \beta b}(1-\rho_a)\hat{a}_t + \frac{\sigma - 1}{\lambda^\sigma - \beta b}V'(L)L\left(\lambda^\sigma\hat{l}_t - \beta b\mathrm{E_t}\hat{\mathrm{l}}_{\mathrm{t+1}}\right), \tag{A54}$$

$$-\hat{U}_{lt} = \frac{1-\sigma}{\lambda - b}(\lambda\hat{c}_t - b\hat{c}_{t-1}) + \left[(\sigma-1)V'(L)L + \eta\right]\hat{l}_t, \tag{A55}$$

$$m\hat{r}s_t = -\hat{U}_{lt} - \hat{U}_{ct}. \tag{A56}$$

Equation (A33) is the Phillips-curve relation in the consumption goods sector that incorporates partial dynamic indexation. In the special case without indexation (i.e., $\eta_c = 0$), this relation reduces to the standard forward-looking Phillips curve relation, under which the price inflation depends on the current-period real marginal cost and the expected future inflation. In the presence of dynamic indexation, the price inflation also depends on its own lag. Equation (A34) is the investment-goods sector Phillips curve, with a similar interpretation. Equation (A35) is the wage Phillips curve, where $\hat{mrs}_t$ denotes the marginal rate of substitution between leisure and consumption.

Equation (A38) describes the law of motion of the relative price of investment goods. Equation (A39) is the linearized investment decision equation with Δ denoting the first-difference operator (so that $\Delta x_t = x_t - x_{t-1}$). Equation (A40) is the linearized capital Euler equation, where

$$r_k = \frac{\lambda^{\sigma-1}\gamma_i}{\beta} - (1-\delta). \tag{A57}$$

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Equation (A41) is the linearized capacity utilization decision equation with $\sigma_u \equiv \frac{a''(1)}{a'(1)}$ denoting the curvature the function evaluated at the steady state. Equation (A42) is the linearized bond Euler equation. Equation (A43) is the linearized law of motion for the capital stock. Equation (A44) is the linearized market-clearing condition in the consumption sector, with $c_y = \frac{\tilde{C}}{\tilde{Y}_c}$. Equation (A45) is the market-clearing condition in the investment sector, with $s_u = \frac{r_k \tilde{K}}{\gamma_i \tilde{I}}$. The steady-state equilibrium conditions imply that

$$s_u = \frac{\frac{\lambda^{\sigma-1}\gamma_i}{\beta} - (1-\delta)}{\gamma_i - (1-\delta)}, \tag{A58}$$

where we have used the steady-state condition that $\frac{\gamma_i \tilde{I}}{\tilde{K}} = \gamma_i - (1-\delta)$ derived from the capital law of motion.

Equations (A46) and (A47) are the linearized market clearing conditions for labor and capital. Equations (A48) and (A49) are the linearized factor demand relations. Equations (A50) and (A51) are the linearized aggregate production functions in the two sectors, with μ_c and μ_i denoting the steady-state markups. Since firms cover average fixed cost using economic profits from markup pricing, aggregate production technology in each sector exhibits increasing returns. Equation (A52) is the linearized real GDP relation. Equation (A53) is the linearized interest rate rule. The next two equations (A54) and (A55) are the linearized marginal utilities of consumption and leisure around the steady state. The parameter $\eta \equiv \frac{V''(L)L}{V'}$ denotes the inverse Frisch elasticity of labor hours (when consumption is held constant). The last equation (A56) gives the marginal rate of substitution between leisure and consumption.

There are 24 endogenous variables summarized in the vector

$$[\hat{\pi}_{ct}, \hat{v}_{ct}, \hat{\pi}_{it}, \hat{v}_{it}, \hat{w}_t, \hat{q}_{it}, \hat{i}_t, \hat{q}_{kt}, \hat{r}_{kt}, \hat{c}_t, \hat{k}_t, \hat{u}_t, \hat{y}_t, \hat{y}_{ct}, \hat{y}_{it}, \hat{k}_{ct}, \hat{k}_{it}, \hat{l}_{ct}, \hat{l}_{it}, \hat{l}_t, \hat{R}_t, \hat{U}_{ct}, \hat{U}_{lt}, \hat{mrs}_t].$$

We solve for the equilibrium dynamics for these 24 endogenous variables using the 24 equations in (49)-(A56), given the shock processes.

Table 1. BFFK Regression Results

Variable	Technology shocks						
	Equipment and consumer durables			Consumption (non-dur. and serv.)			
	dz_{Equip}	dz_{Equip}(-1)	dz_{Equip}(-2)	dz_C	dz_C(-1)	dz_C(-2)	R^2
GDP	-0.70	-0.28	0.25	0.73	0.66	-0.28	0.57
	(0.15)	(0.09)	(0.18)	(0.20)	(0.26)	(0.19)	
Investment	-2.66	-1.91	1.13	1.33	2.14	-1.16	0.34
(equip and Software)	(0.81)	(0.61)	(0.58)	(0.90)	(0.85)	(0.89)	
Consumption	-0.30	-0.05	-0.01	0.35	0.28	0.15	0.65
(non-dur. and services)	(0.12)	(0.07)	(0.11)	(0.13)	(0.14)	(0.16)	
Hours	-0.74	-0.49	0.29	0.00	0.65	-0.38	0.41
	(0.24)	(0.17)	(0.24)	(0.30)	(0.32)	(0.30)	
Relative price	-0.12	0.01	0.11	-0.33	-0.09	-0.24	0.03
of consumption	(0.16)	(0.09)	(0.12)	(0.12)	(0.12)	(0.17)	

Note: Regressions of variable in row on current and 2 lags of final-use technology shocks (shown in columns) from Basu, Fernald, Fisher, and Kimball (2011). dz_{Equip} is the investment technology shock and dz_C is the consumption technology shock as identified by BFFK.

TABLE 2. Calibration of structural parameters

Parameter	Description	Value
	Technologies	
α_c	Cost share of capital in C-sector	0.33
α_i	Cost share of capital in I-sector	0.33
γ_c	Growth rate of C-sector technology	1.0043
γ_i	Growth rate of I-sector technology	1.01
θ_w	Elasticity of substitution between differentiated labor skills	6
θ_c	Elasticity of substitution between differentiated goods in C-sector	10
θ_i	Elasticity of substitution between differentiated goods in I-sector	10
δ	Capital depreciation rate	0.033
σ_u	Curvature of capacity utilization function	2.26
$S''(\lambda_I)$	Curvature of investment adjustment cost function	5.00
	Preferences	
β	Subjective discount factor	0.9962
b	Habit persistence parameter	0.70
σ	Inverse elasticity of intertemporal substitution	3
η	Inverse Frisch elasticity	0.5
L	Steady-state hours worked (targeted)	0.3
	Nominal rigidities	
ξ_c	Calvo probability of sticky prices in C-sector	0.75
ξ_i	Calvo probability of sticky prices in I-sector	0.75
ξ_w	Calvo probability of sticky nominal wages	0.75
η_c	Dynamic indexation parameter in C-sector	0.22
η_i	Dynamic indexation parameter in I-sector	0.22
η_w	Dynamic indexation parameter for wage setting	0.59
	Monetary policy	
ϕ_π	Coefficient for inflation in Taylor rule	1.50
ϕ_y	Coefficient for output in Taylor rule	0.10

Table 3. Calibration of shock parameters

Parameter	Description	Value
ρ_a	Persistence of intertemporal preference shock	0.95
$\rho_{\mu w}$	Persistence of wage-markup shock	0.95
$\rho_{\mu c}$	Persistence of price-markup shock in C-sector	0.95
$\rho_{\mu i}$	Persistence of price-markup shock in I-sector	0.95
ρ_{zc}	Persistence of technology shock in C-sector	0.85
ρ_{zi}	Persistence of technology shock in I-sector	0.94
ρ_χ	Persistence of the marginal efficiency of investment shock	0.95
ρ_g	Persistence of government spending shock	0.95
σ_a	Standard deviation of intertemporal preference shock	0.01
$\sigma_{\mu w}$	Standard deviation of wage-markup shock	0.01
$\sigma_{\mu c}$	Standard deviation of price-markup shock in C-sector	0.01
$\sigma_{\mu i}$	Standard deviation of price-markup shock in I-sector	0.01
σ_{zc}	Standard deviation of technology shock in C-sector	0.838
σ_{zi}	Standard deviation of technology shock in I-sector	1.00
σ_χ	Standard deviation of the marginal efficiency of investment shock	0.01
σ_g	Standard deviation of government spending shock	0.01
σ_r	Standard deviation of monetary policy shock	0.01
$\phi_{\mu w}$	Moving average coefficient for wage-markup shock	0.88
$\phi_{\mu c}$	Moving average coefficient for price-markup shock in C-sector	0.74
$\phi_{\mu i}$	Moving average coefficient for price-markup shock in I-sector	0.74
ρ_{gz}	Reaction of government spending to C-sector technology shocks	0.52

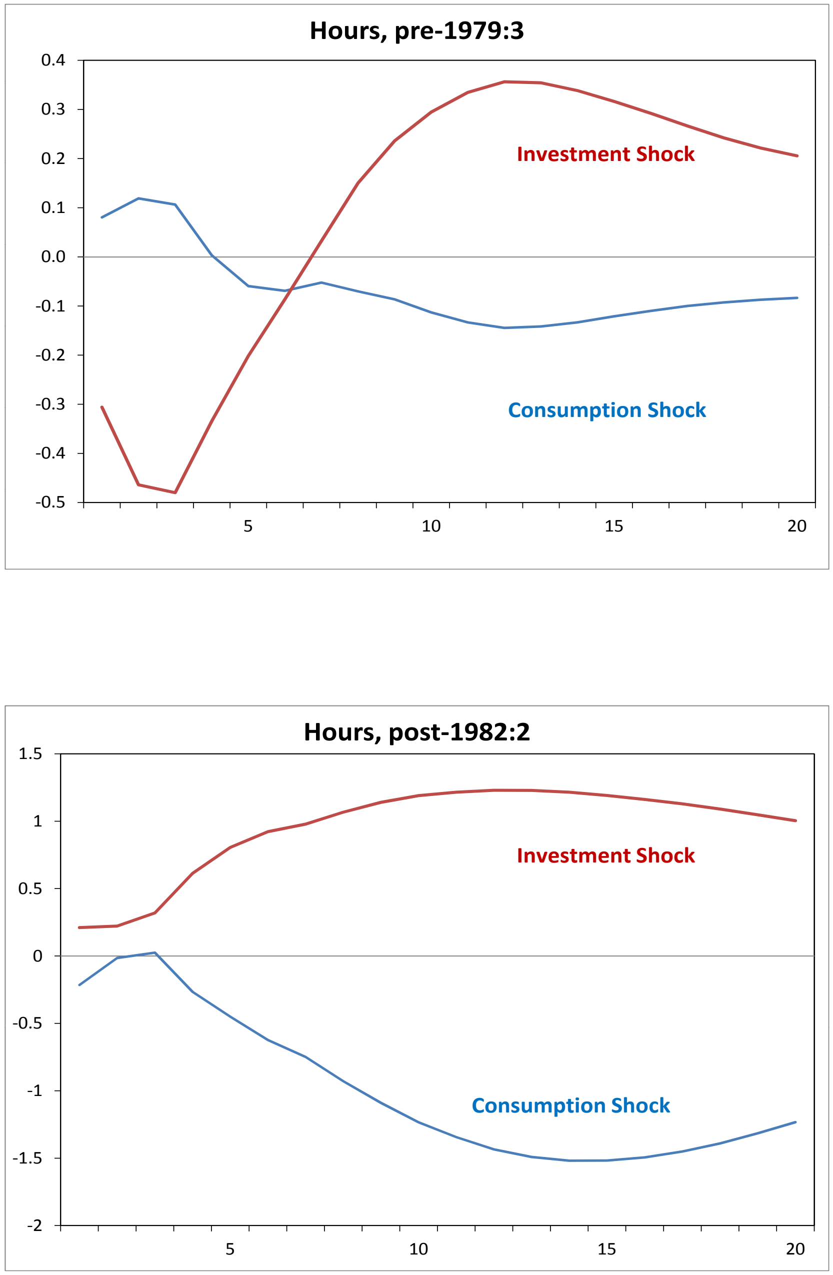

FIGURE 1. Impulse responses of labor hours following sector-specific technology shocks: Fisher (2006) identification. Response to a consumption shock is measured as the difference between the response to a neutral and an investment-specific shock.

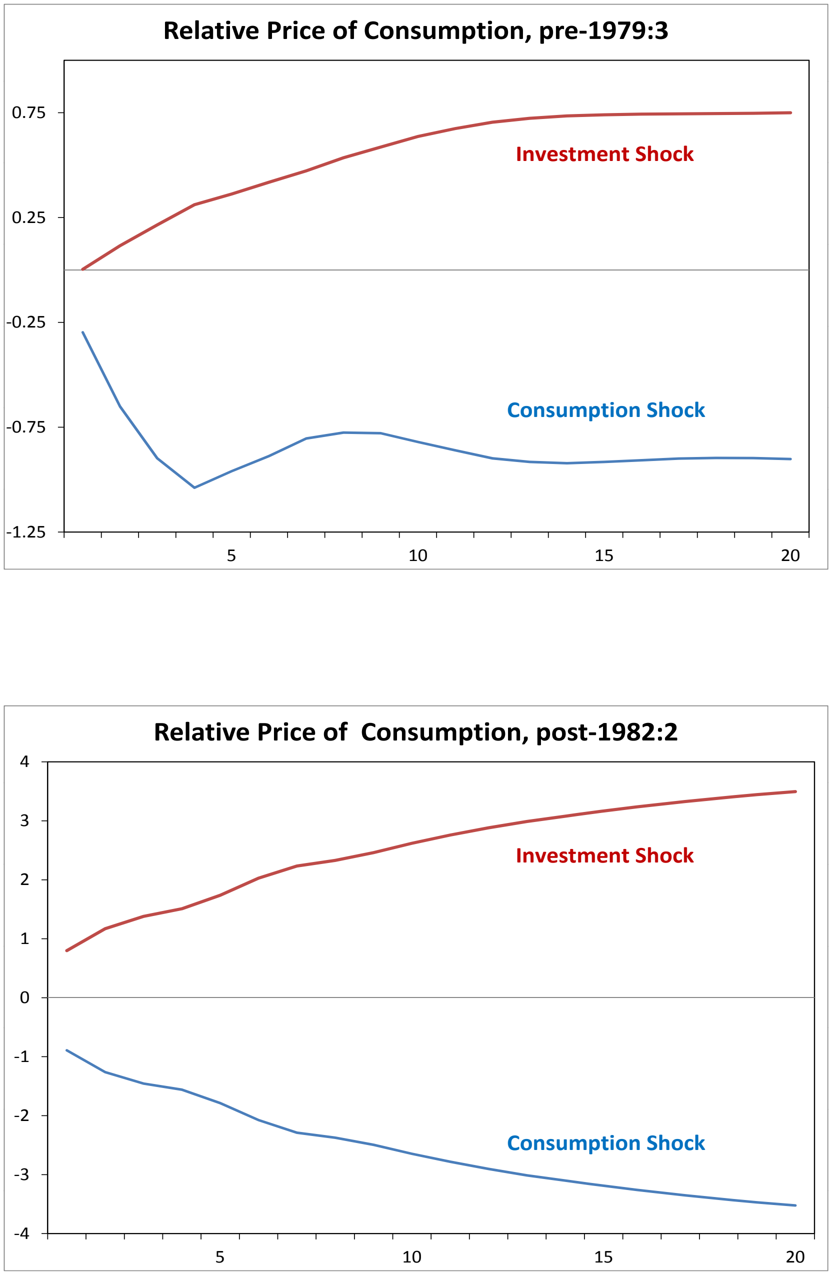

FIGURE 2. Impulse responses of the relative price of consumption goods following sector-specific technology shocks: Fisher (2006) identification. Response to a consumption shock is measured as the difference between the response to a neutral and an investment-specific shock.

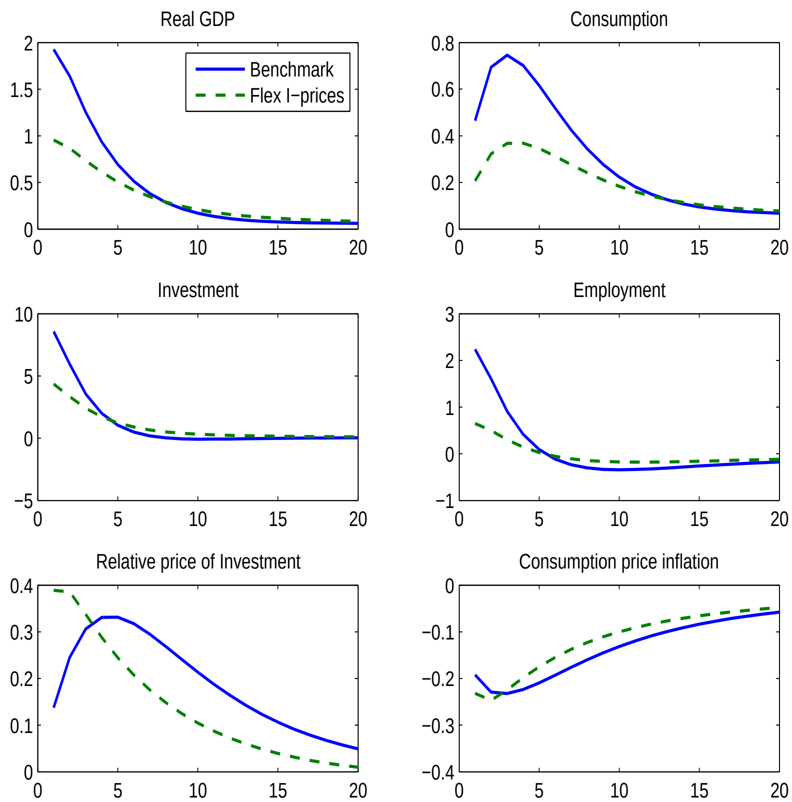

FIGURE 3. Impulse responses following a C-sector technology shock.

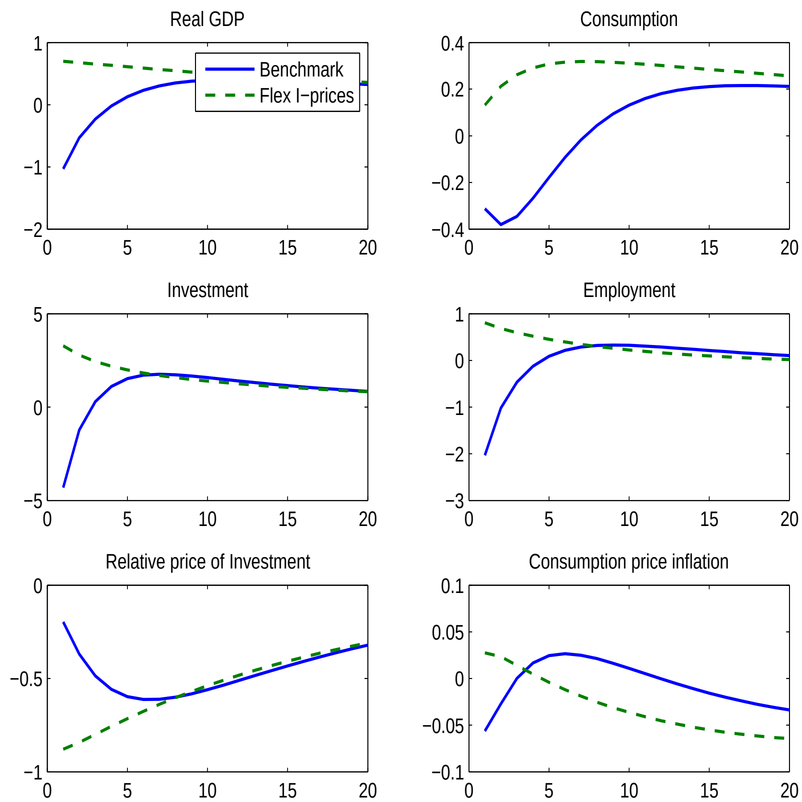

FIGURE 4. Impulse responses following an I-sector technology shock.

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