

# MONETARY NON-NEUTRALITY IN A MULTISECTOR MENU COST MODEL\*

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Empirical evidence suggests that as much as one-third of the U.S. business cycle is due to nominal shocks. We calibrate a multisector menu cost model using new evidence on the cross-sectional distribution of the frequency and size of price changes in the U.S. economy. We augment the model to incorporate intermediate inputs. We show that the introduction of heterogeneity in the frequency of price change triples the degree of monetary non-neutrality generated by the model. We furthermore show that the introduction of intermediate inputs raises the degree of monetary non-neutrality by another factor of three, without adversely affecting the model's ability to match the large average size of price changes. A single-sector model with a frequency of price change equal to the median, rather than the mean, generates monetary non-neutrality similar to that in our multisector model. Our multisector model with intermediate inputs generates variation in real output in response to calibrated aggregate nominal shocks that can account for roughly 23% of the U.S. business cycle.

## I. INTRODUCTION

Much applied work in monetary economics relies on models in which nominal rigidities are the key friction that generates monetary non-neutrality. The workhorse models in this literature—for example, the Taylor (1980) model and the Calvo (1983) model—make the simplifying assumption that the timing of price changes is independent of firms' incentives to change prices. It has been recognized at least since Caplin and Spulber (1987) that models based on this assumption can yield conclusions about monetary non-neutrality very different from models in which nominal rigidities arise due to a fixed cost of changing prices (see also Caballero and Engel [1991, 1993]; Caplin and Leahy [1991, 1997]; Danziger [1999]; Dotsey, King, and Wolman [1999]). Golosov and Lucas (2007) calibrate a menu cost model based on newly available micro-data on the frequency and size of price changes and conclude that nominal rigidities due to menu costs yield monetary non-neutrality that is “small and transient.”

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Given the importance of nominal rigidities as a source of monetary non-neutrality in most models that analyze the transmission of monetary policy, this conclusion poses a serious challenge to monetary economics. If realistically modeled nominal rigidity yields monetary non-neutrality that is small and transient, much of our understanding of the transmission of monetary policy is called into question. It is therefore of great importance for monetary economics to assess whether the implications of highly stylized menu cost models hold up in a richer, more realistic setting.

Monetary economists have long relied heavily on strategic complementarity in price setting to amplify the degree of monetary non-neutrality generated by nominal rigidities. One natural response to Golosov and Lucas's (2007) paper is therefore simply to ramp up the degree of strategic complementarity between price setters. However, recent work has cast doubt on this method of amplification in models with nominal rigidities by showing that the introduction of several popular sources of strategic complementarity renders the models unable to match the average size of micro-level price changes for plausible parameter values (Burstein and Hellwig 2006; Klenow and Willis 2006; Golosov and Lucas 2007).

In this paper, we address both of these challenges. We extend a simple benchmark menu cost model to include two features for which there exists particularly clear empirical evidence: (1) heterogeneity across sectors in the frequency and size of price changes (Figure I) and (2) intermediate inputs. We show that when we subject our model to calibrated nominal shocks, it generates fluctuations in real output that can account for 23% of the U.S. business cycle.<sup>1</sup>

This result of our model accords well with empirical evidence on the importance of nominal shocks for business cycle fluctuations. Shapiro and Watson (1988) attribute 28% of the variation in output at short horizons to nominal shocks.<sup>2</sup> In contrast, the Golosov and Lucas (2007) model generates fluctuations of real

1. Here we compare the variance of real output generated in the model in response to nominal shocks with the variance of Hodrick–Prescott (HP)-filtered real GDP.

2. In fact, Shapiro and Watson (1988) refer to these shocks as “demand” shocks. We follow Lucas (2003) in interpreting them as “nominal” shocks. As Lucas (2003) discusses, these shocks capture not only monetary shocks, but also temporary monetary non-neutrality due to real shocks. Monetary shocks themselves are commonly estimated to account for a relatively modest fraction of business cycle variation in output (see, e.g., Cochrane [1994]; Smets and Wouters [2007]). More comprehensive measures of monetary non-neutrality are higher. The estimates of Justiniano and Primiceri (2008a) imply that more than two-thirds of business cycle fluctuations are due to monetary non-neutrality.

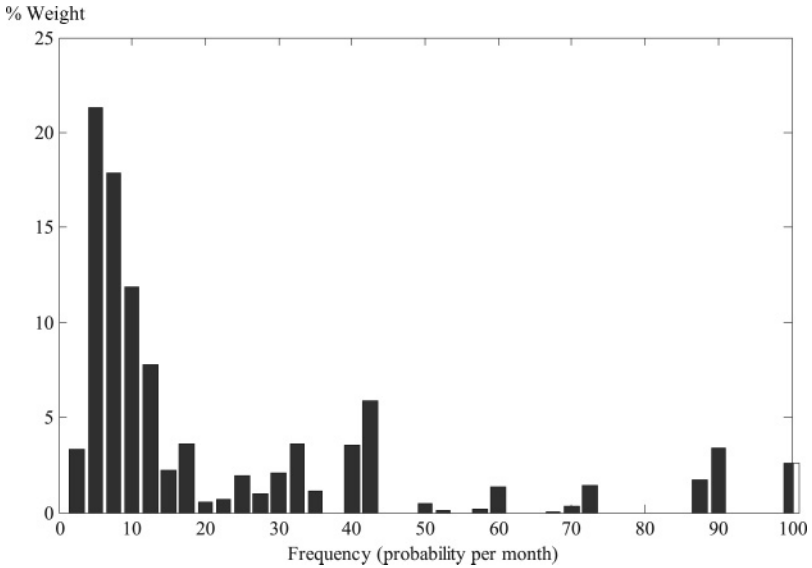


FIGURE I

The Distribution of the Frequency of Price Change for U.S. Consumer Prices

This figure presents a histogram of the cross-sectional distribution of the frequency of nonsale price changes in U.S. consumer prices for the period 1998–2005 (percent per month). The figure is based on the statistics in Nakamura and Steinsson (2008). It is based on the individual price quotes underlying the U.S. CPI. The figure shows the expenditure weighted distribution of the frequency of price changes across entry-level items (ELIs) in the CPI.

output that can account for only roughly 2% of the U.S. business cycle. Roughly half of the difference in monetary non-neutrality in our model relative to the model of Golosov and Lucas (2007) is due to the introduction of heterogeneity in the frequency of price change; the remaining half is due to the introduction of intermediate inputs.

Importantly, our model has no trouble matching the average size of price changes even though the introduction of intermediate inputs generates a substantial amount of strategic complementarity in price setting. To explain this, we follow Ball and Romer (1990) and Kimball (1995) in dividing the sources of strategic complementarity into two classes— $\omega$ -type strategic complementarity and  $\Omega$ -type strategic complementarity. We show that models with a large amount of  $\omega$ -type strategic complementarity are unable to match the average size of price changes, whereas this problem does not afflict models with a large amount of  $\Omega$ -type strategic complementarity. The introduction of intermediate inputs

increases the amount of  $\Omega$ -type strategic complementarity. It therefore does not affect the size of price changes or require unrealistic parameter values.

Our multisector model generates three times more monetary non-neutrality than a single-sector model calibrated to the mean frequency of price change. We also calculate the degree of monetary non-neutrality generated by a single-sector model calibrated to the *median* frequency of price change. This calibration of the single-sector model yields a degree of monetary non-neutrality that is quite similar to that of the multisector model. This suggests that researchers who seek to calibrate single-sector models for the U.S. economy should use the median frequency of price change rather than the mean frequency of price change.

To understand the effect that heterogeneity has on the degree of monetary non-neutrality in our model, consider the response of the economy to a permanent shock to nominal aggregate demand. In the Calvo model, the effect of such a shock on output at any given point in time after the shock is inversely proportional to the fraction of firms that have changed their price at least once since the shock occurred. If some firms have vastly higher frequencies of price change than others, they will change their prices several times before the other firms change their prices once. But all price changes after the first one for a particular firm do not affect output on average because the firm has already adjusted to the shock. Because a marginal price change is more likely to fall on a firm that has not already adjusted in a sector with a low frequency of price change, the degree of monetary non-neutrality in the Calvo model is convex in the frequency of price change and heterogeneity therefore amplifies the overall degree of monetary non-neutrality in the economy relative to that in a single-sector model calibrated to the mean frequency of price change (Carvalho 2006).

The relationship between the frequency of price change and the degree of monetary non-neutrality is more complicated in a menu cost model because firms are not selected at random to change their prices. In menu cost models, the difference in monetary non-neutrality between two sectors will depend not only on their relative frequencies of price change but also on what underlying differences cause the sectors to have different frequencies of price change. Caplin and Spulber (1987) analyze an extreme case in which changes in the size of price changes completely offset changes in the frequency of price change and money is completely neutral regardless of the frequency of price change. We show that

the degree of amplification due to heterogeneity depends critically on the relationship between the frequency of price change and the size of price changes across sectors in the menu cost model more generally. Intuitively, heterogeneity in characteristics such as the size of price changes can cause variation in the strength of the “selection effect” across sectors that can offset variation in the frequency of price change across sectors. We furthermore show that the degree of amplification due to heterogeneity varies with the economy’s average frequency of price change.

Our conclusion that heterogeneity amplifies the degree of monetary non-neutrality by roughly a factor of three for our multisector menu cost model is driven by three features of the U.S. data: (1) the low average level of inflation in the U.S. economy, (2) the fact that the average size of price changes is large and that there is no strong correlation between the size and frequency of price change across sectors, and (3) the relatively low average frequency of price change in the U.S. economy. We perform a number of counterfactual simulations to illustrate these results. Under alternative assumptions about the inflation rate and the size of idiosyncratic shocks (inconsistent with U.S. data), heterogeneity in the frequency of price change yields minimal amplification of monetary non-neutrality. This contrasts with the Calvo model, in which heterogeneity in the frequency of price change amplifies monetary non-neutrality, irrespective of these other characteristics of the economy.

The other feature that amplifies the degree of monetary non-neutrality in our model is intermediate inputs. As in earlier models with time-dependent price setting, introducing intermediate inputs amplifies the degree of monetary non-neutrality because the intermediate inputs cause the pricing decisions of different firms to become strategic complements (Basu 1995; Huang and Liu 2004; Huang, Liu, and Phaneuf 2004; Huang 2006). Intuitively, in the model with intermediate inputs, firms that change their price soon after a shock to nominal aggregate demand choose to adjust less than they otherwise would because the prices of many of their inputs have not yet responded to the shock.

Midrigan (2006) and Gertler and Leahy (2008) discuss several additional mechanisms that raise the degree of monetary non-neutrality generated by menu cost models. Midrigan (2006) argues that the Golosov–Lucas model overstates the strength of the “selection effect.” He augments the Golosov–Lucas model by allowing for fat-tailed idiosyncratic shocks and multiproduct firms

with scale economies in changing prices. He shows that these features mute the selection effect and thereby increase monetary non-neutrality. The empirical importance of these features depends on the extent to which product-level heterogeneity—as opposed to fat-tailed shocks—explains the size distribution of price changes. Gertler and Leahy (2008) analyze a model in which labor markets are assumed to be independent at the sector level. They assume that only firms in a subset of sectors receive idiosyncratic shocks and change their prices in each period. The resulting staggering of price changes across sectors generates  $\Omega$ -type strategic complementarity that amplifies the monetary non-neutrality in their model. However, time series data on the evolution of the frequency of price change in the U.S. economy do not support the notion that the frequency of price change in particular sectors varies greatly over time, even for narrowly defined product categories within the same city. Without a large amount of such time series variation, the Gertler–Leahy model does not generate a quantitatively significant degree of strategic complementarity.

Finally, we consider an extension of our model that incorporates the idea that firms may at times receive opportunities to change their prices at comparatively low cost. We refer to this extended model as the “CalvoPlus” model. These additional low-cost price changes increase the degree of price flexibility in the economy. However, because their timing is not chosen optimally, they induce less price flexibility than the same number of regular price changes. Using this model, we show that introducing a moderate number of time-dependent price changes into a purely state-dependent model has little impact on the overall degree of monetary non-neutrality. Conversely, introducing a small number of state-dependent price changes into a purely time-dependent model has a large effect on the overall degree of monetary non-neutrality.

We argue that new product introductions are an important example of such low-cost price changes. We document that product turnover is by far most important in durable goods sectors such as apparel and automobiles. In these sectors, product introduction is likely to be motivated primarily by factors such as development cycles and changes in consumer tastes—for example, the fall and spring clothing seasons in apparel—that are largely orthogonal to a firm’s desire to change its price. Therefore, the appropriate model of product turnover is likely to be different from the appropriate model of price changes for identical items. We show that if

price changes due to product introduction are primarily motivated by factors other than the firm's desire to change its price, they have only a small effect on the degree of monetary non-neutrality in the model.

Our work builds on a number of earlier papers that investigate the effect of heterogeneity in the frequency of price change in multisector Taylor and Calvo models. Bills and Klenow (2002) analyze the Taylor model and find that heterogeneity amplifies the degree of monetary non-neutrality by a modest amount. Carvalho (2006) considers both the Taylor and Calvo model and several time-dependent sticky information models. He incorporates strategic complementarity into his model and considers a shock process different from that of Bills and Klenow (2002). Carvalho (2006) shows that in time-dependent models the effect of heterogeneity rises with the degree of strategic complementarity. In contrast, we find that in our menu cost model the amplification due to heterogeneity is roughly independent of the degree of strategic complementarity. More recently, Bouakez, Cardia, and Ruge-Murcia (2009a, 2009b) have extended these results to consider heterogeneity along additional dimensions.<sup>3</sup>

Our analysis also builds on the original work on menu cost models in partial equilibrium of Barro (1972), Sheshinski and Weiss (1977), Akerlof and Yellen (1985), Mankiw (1985), and others. The implications of menu costs in general equilibrium have been analyzed analytically in simple models by Caplin and Spulber (1987), Caballero and Engel (1991, 1993), Caplin and Leahy (1991, 1997), Danziger (1999), Dotsey, King, and Wolman (1999), and Gertler and Leahy (2008). Willis (2003), Burstein (2005), Midrigan (2006), and Golosov and Lucas (2007) analyze the implications of menu cost models in general equilibrium using numerical solution methods similar to ours. Finally, we build on a long literature in monetary economics on real rigidities and the use of intermediate inputs by Ball and Romer (1990), Basu (1995), Kimball (1995), Woodford (2003), and others.

The paper proceeds as follows. Section II contains a description of the multisector menu cost model with intermediate inputs. Section III discusses our calibration of the model. Section IV contains our results regarding the effect of heterogeneity on monetary non-neutrality. Section V contains our results on the effect of intermediate inputs on the degree of monetary non-neutrality.

3. See also Aoki (2001).

Section VI contains our results on the effect of product turnover on price flexibility. Section VII contains a discussion of the quantitative importance of our results. Section VIII concludes.

## II. A MULTISECTOR MENU COST MODEL

The model we develop is a multisector generalization of the model presented by Golosov and Lucas (2007) in which firms use intermediate inputs as well as labor as a factor of production.

### II.A. Household Behavior

The households in the economy maximize discounted expected utility, given by

$$(1) \quad E_t \sum_{\tau=0}^{\infty} \beta^{\tau} \left[ \frac{1}{1-\gamma} C_{t+\tau}^{1-\gamma} - \frac{\omega}{\psi+1} L_{t+\tau}^{\psi+1} \right],$$

where  $E_t$  denotes the expectations operator conditional on information known at time  $t$ ,  $C_t$  denotes household consumption of a composite consumption good, and  $L_t$  denotes household supply of labor. Households discount future utility by a factor  $\beta$  per period; they have constant relative risk aversion equal to  $\gamma$ ; and the level and convexity of their disutility of labor are determined by the parameters  $\omega$  and  $\psi$ , respectively.

Households consume a continuum of differentiated products indexed by  $z$ . The composite consumption good  $C_t$  is a Dixit–Stiglitz index of these differentiated goods,

$$(2) \quad C_t = \left[ \int_0^1 c_t(z)^{\frac{\theta-1}{\theta}} dz \right]^{\frac{\theta}{\theta-1}},$$

where  $c_t(z)$  denotes household consumption of good  $z$  at time  $t$  and  $\theta$  denotes the elasticity of substitution between the differentiated goods.

The households must decide each period how much to consume of each of the differentiated products. For any given level of spending in time  $t$ , the households choose the consumption bundle that yields the highest level of the consumption index  $C_t$ . This implies that household demand for differentiated good  $z$  is

$$(3) \quad c_t(z) = C_t \left( \frac{p_t(z)}{P_t} \right)^{-\theta},$$



where  $p_t(z)$  denotes the price of good  $z$  in period  $t$  and  $P_t$  is the price level in period  $t$ , given by

$$(4) \quad P_t = \left[ \int_0^1 p_t(z)^{1-\theta} dz \right]^{\frac{1}{1-\theta}}.$$

The price level  $P_t$  has the property that  $P_t C_t$  is the minimum cost for which the household can purchase the amount  $C_t$  of the composite consumption good.

A complete set of Arrow–Debreu contingent claims is traded in the economy. The budget constraint of the households may therefore be written as

$$(5) \quad P_t C_t + E_t[D_{t,t+1} B_{t+1}] \leq B_t + W_t L_t + \int_0^1 \Pi_t(z) dz,$$

where  $B_{t+1}$  is a random variable that denotes the state-contingent payoffs of the portfolio of financial assets purchased by the households in period  $t$  and sold in period  $t+1$ ,  $D_{t,t+1}$  denotes the unique stochastic discount factor that prices these payoffs in period  $t$ ,  $W_t$  denotes the wage rate in the economy at time  $t$ , and  $\Pi_t(z)$  denotes the profits of firm  $z$  in period  $t$ . To rule out “Ponzi schemes,” we assume that household financial wealth must always be large enough so that future income suffices to avert default.

The first-order conditions of the household’s maximization problem are

$$(6) \quad D_{t,T} = \beta^{T-t} \left( \frac{C_T}{C_t} \right)^{-\gamma} \frac{P_t}{P_T},$$

$$(7) \quad \frac{W_t}{P_t} = \omega L_t^\psi C_t^\gamma,$$

and a transversality condition. Equation (6) describes the relationship between asset prices and the time path of consumption, whereas equation (7) describes labor supply.

## II.B. Firm Behavior

There is a continuum of firms in the economy indexed by  $z$ . Each firm belongs to one of  $J$  sectors and specializes in the production of a differentiated product. The production function of firm  $z$  is given by

$$(8) \quad y_t(z) = A_t(z) L_t(z)^{1-s_m} M_t(z)^{s_m},$$

where  $y_t(z)$  denotes the output of firm  $z$  in period  $t$ ,  $L_t(z)$  denotes the quantity of labor firm  $z$  employs for production purposes in period  $t$ ,  $M_t(z)$  denotes an index of intermediate inputs used in the production of product  $z$  in period  $t$ ,  $s_m$  denotes the materials share in production, and  $A_t(z)$  denotes the productivity of firm  $z$  at time  $t$ . The index of intermediate products is given by

$$M_t(z) = \left[ \int_0^1 m_t(z, z')^{\frac{\theta-1}{\theta}} dz' \right]^{\frac{\theta}{\theta-1}},$$

where  $m_t(z, z')$  denotes the quantity of the  $z'$ th intermediate input used by firm  $z$ .

Following Basu (1995), we assume that all products serve both as final output and as inputs into the production of other products. This “roundabout” production model reflects the complex input–output structure of a modern economy.<sup>4</sup> When the material share  $s_m$  is set to zero, the production function reduces to the linear production structure considered by Golosov and Lucas (2007). Basu (1995) shows that the combination of roundabout production and price rigidity due to menu costs implies that the pricing decisions of firms are strategic complements. In this respect, the roundabout production model differs substantially from the “in-line” production model considered, for example, by Blanchard (1983). The key difference is that in the roundabout model there is no “first product” in the production chain that does not purchase inputs from other firms. The fact that empirically almost all industries purchase products from a wide variety of other industries lends support to the roundabout view of production.<sup>5</sup>

Firm  $z$  in sector  $j$  maximizes the value of its expected discounted profits,

$$(9) \quad E_t \sum_{\tau=0}^{\infty} D_{t,t+\tau} \Pi_{t+\tau}(z),$$

4. See Blanchard (1987) for an earlier discussion of a model with “horizontal” input supply relationships between firms. Huang, Liu, and Phaneuf (2004) use the roundabout production model to explain variation in the cyclicity of real wages over the twentieth century. Huang and Liu (2004) and Huang (2006) investigate the persistence of monetary non-neutrality in a model with roundabout production. These papers all assume staggered price contracts of fixed length.

5. See Basu (1995) for a detailed discussion of this issue.

where profits in period  $t$  are given by

$$(10) \quad \Pi_t(z) = p_t(z)y_t(z) - W_tL_t(z) - P_tM_t(z) - \chi_jW_tI_t(z) - P_tU.$$

Here  $I_t(z)$  is an indicator variable equal to one if the firm changes its price in period  $t$  and zero otherwise. We assume that firms in sector  $j$  must hire an additional  $\chi_j$  units of labor if they decide to change their prices in period  $t$ . We refer to this fixed cost of price adjustment as a “menu cost.” Finally,  $U$  denotes fixed costs the firm must pay to operate. The level of these costs affects the level of profits of the firm as a fraction of output, making it possible to reconcile large markups estimated in the industrial organization literature with small profits in the national accounts. These fixed costs do not affect the firm’s decision problem.

Firm  $z$  must decide each period how much to purchase of each of the differentiated products it uses as inputs. Cost minimization implies that firm  $z$ ’s demand for differentiated product  $z'$  is

$$(11) \quad m_t(z, z') = M_t(z) \left( \frac{p_t(z')}{P_t} \right)^{-\theta}.$$

Combining consumer demand—equation (3)—and input demand—equation (11)—yields total demand for good  $z$ ,

$$(12) \quad y_t(z) = Y_t \left( \frac{p_t(z)}{P_t} \right)^{-\theta},$$

where  $Y_t = C_t + \int_0^1 M_t(z)dz$ . It is important to recognize that  $C_t$  and  $Y_t$  do not have the same interpretations in our model as they do in models that abstract from intermediate inputs. The variable  $C_t$  reflects *value-added* output, whereas  $Y_t$  reflects *gross* output. Because gross output is the sum of intermediate products and final products, it “double-counts” intermediate production and is thus larger than value-added output. GDP in the U.S. National Income and Product Accounts measures value-added output. The variable in our model that corresponds most closely to real GDP is therefore  $C_t$ .

The firm maximizes profits—equation (9)—subject to its production function—equation (8)—demand for its product—equation (12)—and the behavior of aggregate variables. We solve this problem by first writing it in recursive form and then by

employing value function iteration. To do this, we must first specify the stochastic processes of all exogenous variables.

We assume that the log of firm  $z$ 's productivity follows a mean-reverting process,

$$(13) \quad \log A_t(z) = \rho \log A_{t-1}(z) + \epsilon_t(z),$$

where  $\epsilon_t(z) \sim N(0, \sigma_{\epsilon, j}^2)$  are independent. Notice that we assume that the variance of firms' idiosyncratic shocks is sector-specific.

We assume that the monetary authority targets a path for nominal value-added output,  $S_t = P_t C_t$ . Specifically, the monetary authority acts to make nominal value-added output follow a random walk with drift in logs,

$$(14) \quad \log S_t = \mu + \log S_{t-1} + \eta_t,$$

where  $\eta_t \sim N(0, \sigma_\eta^2)$  are independent. We will refer to  $S_t$  either as nominal value-added output or as nominal aggregate demand.<sup>6</sup>

The state space of the firm's problem is infinite-dimensional because the evolution of the price level and other aggregate variables depends on the entire joint distribution of all firms' prices and productivity levels. Following Krusell and Smith (1998), we make the problem tractable by assuming that the firms perceive the evolution of the price level as being a function of a small number of moments of this distribution.<sup>7</sup> Specifically, we assume that firms perceive that

$$(15) \quad \frac{P_t}{P_{t-1}} = \Gamma \left( \frac{S_t}{P_{t-1}} \right).$$

To allow convenient aggregation, we also make use of log-linear approximations of the relationship between aggregate labor supply, aggregate intermediate product output, and aggregate value-added output.

Using the function  $\Gamma$  to form expectations about the price level turns out to be highly accurate. Figure II plots the perceived law of

6. This type of specification for nominal aggregate demand is common in the literature. It can be justified by a model of demand in which nominal aggregate demand is proportional to the money supply and the central bank follows a money growth rule. It can also be justified in a cashless economy (Woodford 2003). In a cashless economy, the central bank can adjust nominal interest rates in such a way as to achieve the target path for nominal aggregate demand. In Section IV, we consider a generalization of the model in which  $S_t$  follows an AR(1) process in growth rates.

7. Willis (2003) and Midrigan (2006) make similar assumptions.

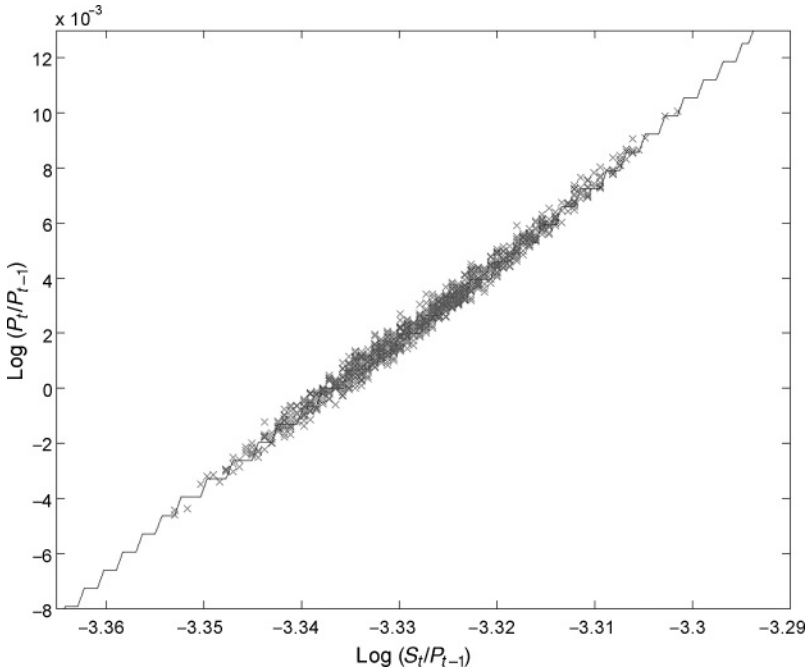


FIGURE II

## Actual Inflation and Perceived Inflation for the Multisector Menu Cost Model

This figure compares actual log inflation (crosses) and perceived log inflation (line) for the multisector menu cost model with intermediate inputs. More specifically, the line represents the perceived aggregate law of motion of  $\log(P_t/P_{t-1})$  as a function of  $\log(S_t/P_{t-1})$ , that is, the function  $\Gamma$ . The crosses denote actual log inflation as a function of  $\log(S_t/P_{t-1})$  in a 1,000-period simulation of our model.

motion for inflation—that is,  $\Gamma$ —as well as the actual log inflation rate as a function of  $\log(S_t/P_t)$  over a 1,000-month simulation of the multisector model using our benchmark calibration.  $\Gamma$  is a step function because we solve the model on a grid for  $\log(S_t/P_t)$ . For over 99% of months, the difference between the perceived law of motion and the actual law of motion is less than one grid point in our discrete approximation of inflation. The approximation errors scale with the size of the grid we use, implying that the errors can be made increasingly small as we raise the number of gridpoints. We have experimented with larger grids and found that this does not affect our results. Krusell and Smith (1998) emphasize the  $R^2$  of a regression of the actual law of motion on the perceived law of motion as a test of accuracy. In our model, the  $R^2$  of a regression of true inflation on perceived inflation is greater than 99%, similar

to the results in Krusell and Smith (1998) and Midrigan (2006). Den Haan (2008) advocates going beyond this test to assess multi-period perception errors by comparing long simulations generated on the one hand entirely using the perceived law of motion ( $\Gamma$ ) and on the other hand entirely using the actual law of motion (simulating the entire model). In a 1,000-period simulation of this type for our model, we find that the root-mean-squared error for both inflation and output is less than one grid point and again scales with the number of gridpoints in our simulation without affecting our results on monetary non-neutrality. For the model reported in Figure II, the root-mean-squared error for inflation is less than five one-hundredths of a percent.

Given these assumptions, firm  $z$ 's optimization problem may be written recursively in the form of the Bellman equation

$$(16) \quad V \left( A_t(z), \frac{p_{t-1}(z)}{P_t}, \frac{S_t}{P_t} \right) = \max_{p_t(z)} \left\{ \Pi_t^R(z) + E_t \left[ D_{t,t+1}^R V \left( A_{t+1}(z), \frac{p_t(z)}{P_{t+1}}, \frac{S_{t+1}}{P_{t+1}} \right) \right] \right\},$$

where  $V(\cdot)$  is firm  $z$ 's value function,  $\Pi_t^R(z)$  denotes firm  $z$ 's profits in real terms at time  $t$ , and  $D_{t,t+1}^R$  denotes the real stochastic discount factor between time  $t$  and  $t + 1$ .<sup>8</sup>

An equilibrium in this economy is a set of stochastic processes for the endogenous price and quantity variables discussed above that are consistent with household utility maximization, firm profit maximization, market clearing, and the evolution of the exogenous variables  $A_t(z)$  and  $S_t$ . We use the following iterative procedure to solve for the equilibrium: (1) We specify a finite grid of points for the state variables,  $A_t(z)$ ,  $p_{t-1}(z)/P_t$  and  $S_t/P_t$ . (2) We propose a function  $\Gamma(S_t/P_{t-1})$  on the grid. (3) Given the proposed  $\Gamma$ , we solve for the firm's policy function  $F$  by value function iteration on the grid. (4) We check whether  $\Gamma$  and  $F$  are consistent.<sup>9</sup> If so, we stop and use  $\Gamma$  and  $F$  to calculate other features of the equilibrium. If not, we update  $\Gamma$  and go back to step (3). We

8. In Online Appendix A, we show how the firm's real profits can be written as a function of  $(A_t(z), p_{t-1}(z)/P_t, S_t/P_t)$  and  $p_t(z)$ .

9. We do this in the following way: First, we calculate the stationary distribution of the economy over  $(A(z), p(z)/P, S/P)$  implied by  $\Gamma$  and  $F$  as described in Online Appendix B. Second, we use the stationary distribution and equation (4) to calculate the price index implied by  $\Gamma$ —call it  $P_\Gamma$ —for each value of  $S/P$ . Third, we check whether  $|P_\Gamma - P| < \xi$ , where  $|\cdot|$  denotes the sup-norm.

approximate the stochastic processes for  $A_t(z)$  and  $S_t$  using the method proposed by Tauchen (1986).<sup>10</sup>

### *II.C. The CalvoPlus Model*

Much applied work in monetary economics relies on models in which the timing of price changes is independent of firms' incentives to change prices. Such price changes are said to be "time-dependent." In this section, we describe an extension of our menu cost model in which a fraction of price changes are largely time-dependent. We introduce this model as a benchmark for comparison with our baseline state-dependent model. In Section VI, we also use this model to assess the sensitivity of our baseline menu cost model to the introduction of price flexibility due to product turnover.

The most widely used model of time-dependent price changes is the model of Calvo (1983).<sup>11</sup> In this model, firms receive an opportunity to change their prices at no cost with probability  $(1 - \alpha)$ , but otherwise price changes are infinitely costly. These extreme assumptions make the Calvo model highly tractable. However, they also cause the model to run into severe trouble in the presence of large idiosyncratic shocks or a modest amount of steady-state inflation.<sup>12</sup> In such models, the firm's desire to change its price may become very large and it may prefer to shut down rather than continue producing at its preset price.

10. A drawback of numerical methods of the type we employ in this paper is that it is difficult to prove uniqueness. The main feature of our model that potentially could generate nonuniqueness is the combination of strategic complementarity and menu costs (Ball and Romer 1991). However, the large idiosyncratic shocks that we assume in our model significantly reduce the scope for multiplicity (Caballero and Engel 1993). In particular, the type of multiplicity studied by Ball and Romer does not exist in our model because the large idiosyncratic shocks prevent sufficient synchronization across firms. In this respect our results are similar to those of John and Wolman (2004). It is also conceivable that our use of Krusell and Smith's approximation method could yield self-fulfilling approximate equilibria. There is, however, nothing in the economic link between agents' beliefs and their pricing decisions that suggests such self-fulfilling equilibria. In fact, the actual behavior of the price level in our model is quite insensitive to even relatively large changes in beliefs. The reason for this is that by far the most important factor in agents' decisions is movements in their idiosyncratic productivity levels as opposed to movements in aggregate variables. We solved our model with more sophisticated beliefs (additional moments) and starting our fixed point algorithm at various initial values. In all cases the resulting approximate fixed point is virtually identical.

11. Examples of papers that use the Calvo model include Clarida, Gali, and Gertler (1999) and Christiano, Eichenbaum, and Evans (2005). An alternative time-dependent price setting model was proposed by Taylor (1980). This model has been used, for example, by Chari, Kehoe, and McGrattan (2000).

12. See Bakhshi et al. (2007) for an analysis of the latter issue.

TABLE I  
BENCHMARK PARAMETERS

Discount factor	$\beta = 0.96^{1/12}$
Coefficient of relative risk aversion	$\gamma = 1$
Inverse of Frisch elasticity of labor supply	$\psi = 0$
Elasticity of demand	$\theta = 4$
Steady-state labor supply	$L = 1/3$
Intermediate inputs share in production	$s_m = 0.7$
Speed of mean reversion of idiosyncratic productivity	$\rho = 0.7$
Mean growth rate of nominal aggregate demand	$\mu = 0.0028$
Std. deviation of the growth rate of nominal aggregate demand	$\sigma_\eta = 0.0065$

Rather than assuming that price changes are either free or infinitely costly, we assume that with probability  $(1 - \alpha)$  the firms receive an opportunity to change their prices at a relatively low cost  $\chi_{j,l}$ , whereas otherwise they face a high menu cost  $\chi_{j,h}$ . These assumptions retain the tractability of the Calvo model. But at the same time they capture the idea that the timing of some price changes—those that occur when the firm receives the low-cost repricing opportunities—is largely orthogonal to the firm’s desire to change its price. We refer to this model as the “CalvoPlus” model. The CalvoPlus model has the appealing feature that it nests both the Calvo model and the menu cost model as special cases.<sup>13</sup>

### III. CALIBRATION

We focus attention on the behavior of the economy for a specific set of parameter values. Table I reports our benchmark parameter values. We set the monthly discount factor equal to  $\beta = 0.96^{1/12}$ . We assume log utility in consumption ( $\gamma = 1$ ). Following Hansen (1985) and Rogerson (1988), we assume linear disutility of labor ( $\psi = 0$ ). The most important way in which these parameters affect our results is through the elasticity of the real wage with respect to output.

13. Our CalvoPlus model is related to the random menu cost model analyzed by Dotsey, King, and Wolman (1999) and Caballero and Engel (2006). It is also related to the model developed by Midrigan (2006). Midrigan augments the Golosov–Lucas model by allowing for fat-tailed idiosyncratic shocks and multi-product firms with scale economies in changing prices. These features imply that the hazard of price change is much less strongly related to the firm’s price relative to its desired price, muting the selection effect as in our CalvoPlus model.



We set  $\omega$  so that in the flexible-price steady state, labor supply is  $1/3$ . We set  $\theta = 4$  to roughly match estimates of the elasticity of demand from the industrial organization and international trade literatures.<sup>14</sup> Our choices of  $\mu = 0.0028$  and  $\sigma_\eta = 0.0065$  are based on the behavior of U.S. nominal and real GDP during the period 1947–2005.<sup>15</sup> Because our model does not incorporate a secular trend in economic activity, we set  $\mu$  equal to the mean growth rate of nominal GDP less the mean growth rate of real GDP. We set  $\sigma_\eta$  equal to the standard deviation of nominal GDP growth.

We calibrate the size of the menu cost and the variance of the idiosyncratic shocks in each sector of our model based on empirical evidence on the frequency and size of price changes excluding sales in consumer prices across sectors of the U.S. economy presented in Nakamura and Steinsson (2008).<sup>16</sup> We group goods with similar price change characteristics into six, nine, and fourteen sectors. Table II presents the mean frequency and mean absolute size of price changes for these sectors.<sup>17</sup> Both the frequency and the size of price changes varies enormously across sectors. There is no simple relationship between these two variables (see Figure III). Furthermore, the distribution of the frequency of price change is highly asymmetric, the right tail being much longer than the left tail (Figure I). This skewness implies that the mean frequency of price change across sectors is much higher than the

14. Berry, Levinsohn, and Pakes (1995) and Nevo (2001) find that markups vary a great deal across firms. The value of  $\theta$  we choose implies a markup similar to the mean markup estimated by Berry, Levinsohn, and Pakes (1995) but slightly below the median markup found by Nevo (2001). Broda and Weinstein (2006) estimate elasticities of demand for a large array of disaggregated products using trade data. They report a median elasticity of demand below three. Also, Burstein and Hellwig (2006) estimate an elasticity of demand near five using a menu cost model. Midrigan (2006) uses  $\theta = 3$ , whereas Golosov and Lucas (2007) use  $\theta = 7$ . The value of  $\theta$  affects our calibration of the menu cost—a higher  $\theta$  implies higher menu costs—and it affects our calibration of the intermediate input share—a higher  $\theta$  implies lower values for  $s_m$ . Holding fixed the frequency of price change and the intermediate input share, the value of  $\theta$  does not affect the degree of monetary non-neutrality in our model.

15. Our results are virtually identical if we set  $\mu = 0$  rather than  $\mu = 0.0028$ .

16. We have also used the distribution of the frequency of price change including sales. We find that both of these distributions yield similar results regarding amplification of monetary non-neutrality due to heterogeneity. We do not have an analytical proof of unique identification in the multisector model. In numerical simulations, we have found that variation of parameters in one sector has virtually no effect on the size and frequency in other sectors. This implies that the overall model is uniquely identified because the parameters in each sector are uniquely identified.

17. We calibrate the multisector models to the mean frequency and mean absolute size of price change at the sectoral level. The difference between the sectoral mean and median is small.

TABLE II  
SECTOR CHARACTERISTICS FOR MULTISECTOR MODELS

Name	Weight (%)	Freq. (%)	Abs. size (%)	Subs. (%)
Panel A: Six-sector model				
Vehicle fuel, used cars	7.7	91.6	4.9	8.9
Transp. goods, utilities, travel	19.1	35.5	10.9	4.5
Unprocessed food	5.9	25.4	15.9	1.3
Processed food, other goods	13.7	11.9	11.4	2.0
Services (excl. travel)	38.5	8.8	8.3	2.0
Hh. furn., apparel, rec. goods	15.1	5.2	11.1	7.9
Panel B: Nine-sector model				
Vehicle fuel, used cars	7.7	91.6	4.9	8.9
Transp. goods, utilities, travel	19.1	35.5	10.9	4.5
Unprocessed food	5.9	25.4	15.9	1.3
Services (1)	9.2	19.7	4.6	2.1
Processed food, other goods	13.7	11.9	11.4	2.0
Services (2)	9.6	7.6	7.2	3.7
Services (3)	10.0	5.5	8.1	1.3
Hh. furn., apparel, rec. goods	15.1	5.2	11.1	7.9
Services (4)	9.7	3.2	12.8	0.9
Panel C: Fourteen-sector model				
Vehicle fuel, used cars	7.7	91.6	4.9	8.9
Utilities	5.3	49.4	6.4	0.6
Travel	5.5	43.7	18.4	1.8
Unprocessed food	5.9	25.4	15.9	1.3
Transp. goods	8.3	21.3	8.9	8.8
Services (1)	7.7	21.7	4.0	2.2
Processed food, other goods	13.7	11.9	11.4	2.0
Services (2)	7.5	8.4	6.7	4.4
Hh. furn.	5.0	6.5	10.1	5.0
Services (3)	7.8	6.2	8.8	1.7
Rec. goods	3.6	6.1	10.2	5.9
Services (4)	7.6	4.9	8.1	0.9
Apparel	6.5	3.6	12.4	11.3
Services (5)	7.9	2.9	13.5	1.0

*Notes.* This table presents the weighted mean frequency and log absolute size of price changes as well as the frequency of product substitution for U.S. consumer prices over the period 1998–2005 for divisions into six, nine, and fourteen sectors. These statistics are calculated using the methodology described in Nakamura and Steinsson (2008), based on the individual price quotes underlying the U.S. consumer price index (CPI). The weighted means are calculated using CPI expenditure weights for entry level items (ELIs). “Weight” gives the total expenditure weight for the category. “Freq.” gives the weighted mean frequency of price change for the category. “Abs. size” gives the weighted mean absolute size of log price changes for the category. “Subs.” gives the weighted mean frequency of product substitution. See Nakamura and Steinsson (2008) for more details on how these statistics are constructed. In the nine- and fourteen-sector models, the service sector is divided equally into four and five groups, respectively, where the ELIs are sorted into different groups according to the ELI-level frequency of price change.

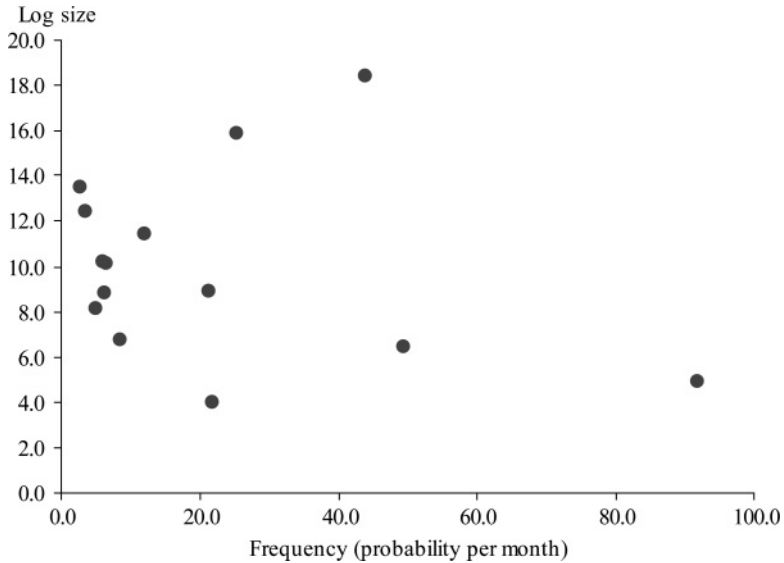


FIGURE III

## The Frequency and Size of Price Changes across Different Sectors

The figure plots the average frequency and size of price changes for each sector in our fourteen-sector model. See Table III for a discussion of the underlying data.

median frequency of price change—21.1% versus 8.7% for 1998–2005.<sup>18</sup>

Table III presents the parameterization of the menu cost and the variance of the idiosyncratic shocks at the sectoral level, which allow the model to match the empirical statistics on the frequency and size of price changes presented in Table II. We report the average yearly cost of changing prices in each sector as a fraction of steady-state revenue. In all cases, the cost of changing prices is less than 1% of revenue, and in most sectors it is less than 0.5%. The cost of changing prices is less than half as large in the model with intermediate inputs as it is in the model without intermediate inputs.

The standard deviations of the idiosyncratic shocks needed to match the size of price changes in the data are quite large. They range from about 3% to about 11%. Figure IV plots a sample path for a “typical” firm in the model with intermediate inputs. The plot

18. In Nakamura and Steinsson (2008), we find a similar pattern for finished goods producer prices. In the producer prices case, the mean is 24.7%, whereas the median is 10.8%.

TABLE III  
PARAMETER VALUES FOR MULTISECTOR MODELS

	Menu cost model			CalvoPlus model		
	$s_m = 0$	$s_m = 0.7$	$s_m = 0$	$s_m = 0$	$s_m = 0.7$	$s_m = 0$
	$\Delta p$ cost $\times 10^{-2}$	$\sigma_\varepsilon$ $\times 10^{-2}$	$\Delta p$ cost $\times 10^{-2}$	$\sigma_\varepsilon$ $\times 10^{-2}$	$\Delta p$ cost $\times 10^{-2}$	$\sigma_\varepsilon$ $\times 10^{-2}$
	Panel A: Six-sector model					
Vehicle fuel, used cars	0.004	5.00	0.001	5.10	0.007	0.001
Transp. goods, utilities, travel	0.309	6.90	0.087	6.85	0.399	0.110
Unprocessed food	0.667	9.10	0.194	9.20	0.967	0.268
Processed food, other goods	0.331	5.70	0.091	5.70	0.516	0.129
Services (excl. travel)	0.165	3.90	0.046	4.05	0.269	0.075
Hh. furn., apparel, rec. goods	0.271	5.46	0.070	5.40	0.446	0.107
	Panel B: Nine-sector model					
Vehicle fuel, used cars	0.004	5.30	0.002	5.40	0.007	0.001
Transp. goods, utilities, travel	0.307	6.90	0.091	7.00	0.399	0.115
Unprocessed food	0.667	9.00	0.185	9.00	0.963	0.234
Services (1)	0.059	2.40	0.019	2.65	0.099	0.022
Processed food, other goods	0.340	5.80	0.093	5.70	0.545	0.132
Services (2)	0.137	3.50	0.035	3.45	0.220	0.065
Services (3)	0.156	3.80	0.042	3.90	0.261	0.070
Hh. furn., apparel, rec. goods	0.306	5.80	0.076	5.40	0.451	0.121
Services (4)	0.340	6.50	0.083	6.39	0.474	0.122

TABLE III  
(CONTINUED)

	Menu cost model			CalvoPlus model		
	$s_m = 0$			$s_m = 0.7$		
	$\Delta p$ cost $\times 10^{-2}$	$\sigma_\varepsilon$ $\times 10^{-2}$	$\Delta p$ cost $\times 10^{-2}$	$\sigma_\varepsilon$ $\times 10^{-2}$	$\Delta p$ cost $\times 10^{-2}$	$\sigma_\varepsilon$ $\times 10^{-2}$
	Panel C: Fourteen-sector model					
Vehicle fuel, used cars	0.005	5.20	0.002	5.20	0.007	5.39
Utilities	0.095	4.65	0.027	4.80	0.112	5.28
Travel	0.636	11.10	0.210	12.00	0.931	14.00
Unprocessed food	0.724	9.40	0.198	9.00	0.969	12.40
Transp. goods	0.244	5.20	0.060	4.71	2.758	6.80
Services (1)	0.069	2.70	0.023	2.97	0.057	3.00
Processed food, other goods	0.322	5.60	0.095	5.75	0.508	9.00
Services (2)	0.117	3.20	0.034	3.30	0.200	0.056
Hh. furn.	0.228	4.80	0.065	4.69	0.405	8.80
Services (3)	0.177	4.10	0.049	4.10	0.298	7.40
Rec. goods	0.239	4.80	0.064	4.80	0.413	8.80
Services (4)	0.159	3.80	0.047	4.00	0.307	7.60
Apparel	0.331	6.05	0.087	5.99	0.537	10.50
Services (5)	0.388	7.01	0.102	6.82	0.528	11.50

Notes. This table presents the cost of changing prices and the volatility of idiosyncratic shocks for the multisector menu cost model and CalvoPlus model both with and without intermediate goods. “ $\Delta p$  cost” denotes the average cost of changing prices in a year as a fraction of steady-state revenue. In the menu cost model this is equal to  $f(\theta - 1)/\theta \times Y_{SS}$ , where  $f$  denotes the frequency of price change and  $Y_{SS}$  is steady-state output under flexible prices. In the CalvoPlus model it is calculated analogously except that the calculation takes into consideration the breakdown of price changes in the high- and low-cost states.  $\sigma_\varepsilon$  is the variance of shocks to the log of the idiosyncratic productivity shocks.  $s_m$  is the fraction of marginal costs accounted for by intermediate goods. In the CalvoPlus model, the fraction of time spent in the “low-menu cost” state is set at  $1 - \alpha = f$  req. for each sector in all cases.

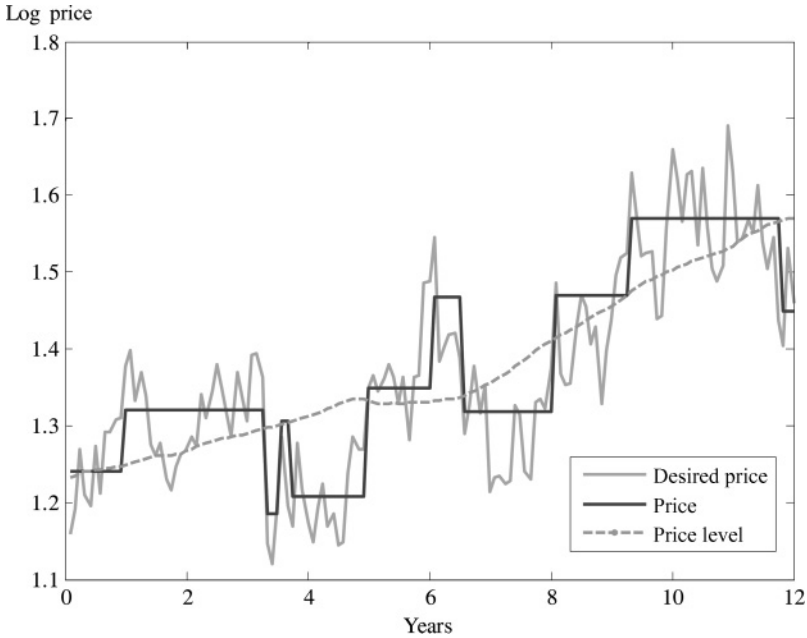


FIGURE IV

## A Sample Path from the Price of a Typical Product

This figure plots a sample path of the price for a single firm in the model with intermediate inputs. The menu cost and variance of idiosyncratic shocks for the firm are set to match the median frequency and size of price changes. It also plots the price level and the firm's static desired price.

illustrates that the standard deviation of the idiosyncratic shocks is many times larger than the standard deviation of the shocks to nominal aggregate demand. As is emphasized by Golosov and Lucas (2007), this is crucial for generating price changes sufficiently large to match the data. It is also crucial for generating the substantial number of price decreases observed in the data.<sup>19</sup> For computational reasons, we set the speed of mean reversion of the firm productivity process equal to  $\rho = 0.7$ . This value is close to the value we estimate for  $\rho$  in Nakamura and Steinsson (2008).

The parameter  $s_m$  denotes the cost share of intermediate inputs in the model. Table IV contains information from the 2002 U.S. Input–Output Table published by the Bureau of Economic

19. Empirical evidence suggests that variation of firm productivity is in fact much smaller than what is implied by our calibration (Abraham and White 2007). The idiosyncratic productivity shocks should therefore be viewed as a stand-in for a broader class of idiosyncratic shocks that cause variation in firms' desired prices.

TABLE IV  
INTERMEDIATE INPUTS IN THE U.S. ECONOMY IN 2002

	% int. inputs	% used	% gross Y	% GDP	% CPI
Agriculture and mining	55.1	5.5	2.4	1.9	0.0
Utilities	36.8	2.6	1.7	2.0	5.3
Construction	46.8	1.5	4.8	4.6	0.0
Manufacturing	64.9	28.8	20.5	12.9	51.2
Trade	31.7	6.2	10.4	12.8	0.0
Services	39.3	53.0	48.7	53.0	43.5
Government	37.9	0.9	11.5	12.8	0.0

*Notes.* These data (except the last column) are from the 2002 “Use” table of the U.S. Annual Input–Output Accounts published by the Bureau of Economic Analysis. The last column is taken from Nakamura and Steinsson (2008). “% int. inputs” denotes the fraction of intermediate inputs in each sector’s gross output. “% used” denotes the fraction of all intermediate inputs in the economy that come from a given sector. “% gross Y” denotes each sector’s weight in gross output. “% GDP” denotes each sector’s weight in GDP. “% CPI” denotes each sector’s weight in the CPI.

Analysis. The table provides information about both the share of intermediate inputs in the gross output of each sector (column (1)) and about how intensively the output of each sector is used as an intermediate input in other sectors (column (2)). The revenue share of intermediate inputs varies from about one-third to about two-thirds. It is highest in manufacturing and lowest in utilities. The use of different sectors as intermediate inputs (column (2)) is closely related to their weight in gross output (column (4)). In particular, services are used heavily as intermediate inputs (accounting, legal, consulting, financial, marketing). The main deviation from this pattern is that the output of manufacturing is used somewhat more intensively as an intermediate input than its weight in gross output would suggest, whereas the output of the government sector and the construction sector is used less.

The weighted average revenue share of intermediate inputs in the U.S. private sector using Consumer Price Index (CPI) expenditure weights was roughly 52% in 2002. The cost share of intermediate inputs is equal to the revenue share times the markup. Our calibration of  $\theta$  implies a markup of 1.33. Our estimate of the weighted average cost share of intermediate inputs is therefore roughly 70%.

This calibration depends on a number of assumptions. Alternative assumptions yield estimates of the intermediate inputs share that are either lower or higher. We employ CPI weights as we do elsewhere in the paper. Using gross output weights would yield a slightly lower number (63% rather than 70%) because

services have a higher weight in gross output than in the CPI. However, increasing the weight of services would also lower the mean frequency of price change and increase the skewness of the frequency distribution. A higher value for the elasticity of demand would also yield a lower intermediate input share. For example, Golosov and Lucas (2007) use  $\theta = 7$ . This would yield an intermediate input share equal to 60% rather than 70%.

We assume that intermediate inputs make up the same fraction of marginal costs as they do of average variable costs. With a more general production structure, this is not necessarily the case. Materials might be disproportionately important at the margin, in which case the share of intermediate inputs in marginal costs would be higher than we estimate. Also, the constant intermediate inputs share that matches the behavior of an economy with heterogeneity in the use of intermediate inputs across sectors is slightly higher than the average  $s_m$  across sectors (see discussion in Section V). Given the uncertainty associated with these factors, we report results for a range of different values for  $s_m$  from 0.5 to 0.9 in Section V.A below.<sup>20</sup>

The assumption of roundabout production implies that prices are rigid to all customers whether they are consumers or firms. Direct evidence on producer prices from Carlton's (1986) work on the Stigler–Kindahl data set as well as Blinder et al.'s (1998) survey of firm managers supports the view that price rigidity is an important phenomenon at intermediate stages of production. In Nakamura and Steinsson (2008), we present a more comprehensive analysis of producer prices based on the micro-data underlying the producer price index and find that the rigidity of producer prices is comparable to the rigidity of nonsale consumer prices. The median frequencies of price change of finished goods and intermediate goods producer prices are 10.8% and 14.3%, respectively, whereas the median frequency of price change of consumer prices is 8.7%. Moreover, we document a high correlation between

20. Basu (1995) and Bergin and Feenstra (2000) argue for values of the parameter  $s_m$  between 0.8 and 0.9. Huang, Liu, and Phaneuf (2004) favor a value of 0.7. Rotemberg and Woodford (1995), Chari, Kehoe, and McGrattan (1996), and Woodford (2003, Ch. 3) use values closer to  $s_m = 0.5$ . The lower values of  $s_m$  are based on much lower calibrations of the markup of prices over marginal costs than we use. These low markups are meant to match the fact that pure profits are a relatively small fraction of GDP in the United States. We base our calibration of the markup of prices over marginal costs on evidence from the industrial organization and international trade literature. These high markups are consistent with low pure profits if firms have fixed costs and/or if firm entry involves sunk investment costs that must be recouped with flow profits post-entry, as in our model (e.g., Dixit and Pindyck [1994]; Ryan [2006]).



TABLE V  
 FREQUENCY OF PRICE CHANGE: COMPARISON OF CPI AND PPI

Category	Number of matches	Frequency of price change	
		CPI	PPI
Processed food	32	10.5	7.2
Unprocessed food	24	25.9	67.9
Hh. furn.	27	6.5	5.6
Apparel	32	3.6	2.7
Rec. goods	16	6.8	6.1
Other goods	13	23.2	17.1

*Notes.* This table presents a comparison between the frequency of price change for consumer prices excluding sales and producer prices over the 1998–2005 period. These statistics are from Nakamura and Steinsson (2008) and are based on the individual price quotes underlying the U.S. consumer price index (CPI) and producer price index (PPI). These statistics are constructed by matching entry-level items (ELIs) in the CPI to four-, six-, or eight-digit commodity codes within the PPI. “Number of matches” denotes the number of such matches that were possible within the major group. “Frequency of price change” denotes the median frequency across categories among the matches found. See Nakamura and Steinsson (2008) for more details on how these statistics are constructed.

the frequency of nonsale consumer price changes and the frequency of producer price changes at a very disaggregated level. This evidence is reproduced in Table V. Over the 153 matches, the correlation between the frequency of price change for producer prices and consumer prices excluding sales is 0.83.

Our baseline model abstracts from capital accumulation. However, in Online Appendix C we develop a model with capital to assess the effect that capital has on our results. The main way in which introducing capital into our model affects our results is by affecting the variability of marginal costs and thus the degree of real rigidity in the model. In the baseline model with intermediate inputs, the elasticity of marginal costs with respect to output is equal to  $1 - s_m = 0.3$ . In Online Appendix C, we derive an upper bound of 0.38 for the elasticity of marginal costs with respect to output in the model with capital. The empirical results of Solon, Barsky, and Parker (1994) on the cyclicalities of real wages suggest that for the U.S. economy the elasticity of real wages with respect to output is in fact only about 0.6. Our baseline calibration assumes unit elasticity of the real wage with respect to output, somewhat overstating the response of real wages relative to empirical evidence. If we incorporate Solon, Barsky, and Parker’s empirical estimate for the wage elasticity into our model with capital, we get an elasticity of marginal cost of 0.28. This is almost exactly equal to the elasticity of 0.3 that we assume in our baseline model. In other words, we have adopted a baseline

TABLE VI  
HETEROGENEITY AND MONETARY NON-NEUTRALITY

	Menu cost model		CalvoPlus model	
	$s_m = 0$	$s_m = 0.7$	$s_m = 0$	$s_m = 0.7$
Monetary non-neutrality: $\text{Var}(C_t)$				
One-sector model (mean)	0.055	0.182	0.173	0.461
Six-sector model	0.136	0.470	0.458	1.492
Nine-sector model	0.143	0.576	0.495	1.563
Fourteen-sector model	0.188	0.627	0.520	1.709
One-sector model (median)	0.261	0.658	0.625	1.480

*Notes.* This table presents estimates of the variance of real value-added output for the multisector menu cost model and the multisector CalvoPlus model for two values of the intermediate inputs share ( $s_m$ ). The variance of real value-added output is multiplied by  $10^4$ . The first two columns present results for the menu cost model. The third and fourth columns present results for the CalvoPlus model. See Table IV for the parameter values assumed in these models.

specification that implies an elasticity of marginal costs similar to what is implied by a model with capital and calibrated to match the empirical evidence presented in Solon, Barsky, and Parker (1994). We discuss this in detail in Online Appendix C. For parsimony and comparability with earlier work—for example, Golosov and Lucas (2007)—we choose the model without capital as our baseline specification.

#### IV. HETEROGENEOUS PRICE RIGIDITY AND MONETARY NON-NEUTRALITY

Our primary interest is in the degree of monetary non-neutrality generated by the menu cost model. Table VI presents estimates of this for a number of different calibrations of the model. We measure the degree of monetary non-neutrality as the variance of real value-added output when the model is simulated with purely nominal aggregate shocks.<sup>21</sup> We first consider the behavior of the menu cost model with the intermediate input share set to zero. We will consider the effect of introducing intermediate inputs in Section V.

21. This measure of monetary non-neutrality has been used, for example, by Midrigan (2006). An alternative measure of monetary non-neutrality is the cumulative impulse response of real value-added output to a permanent shock to nominal aggregate demand. If our model were log-linear and delivered an AR(1) response of real output to a permanent shock to nominal aggregate demand, these measures would be proportional. We have calculated the CIR for all cases presented in the paper, and the results using this alternative measure are practically identical.

The first column of Table VI presents results for our six-, nine-, and fourteen-sector models, as well as two calibrations of a single-sector version of our model. The degree of monetary non-neutrality is sharply increasing in the number of sectors. The fourteen-sector model generates roughly three times as much monetary non-neutrality as the single-sector model that is calibrated to match the mean frequency of price change.<sup>22</sup> The table also reports results for the single-sector model calibrated to match the median frequency of price change. This calibration of the single-sector model yields a degree of monetary non-neutrality that is more similar to that in the multisector model than does the single-sector model calibrated to match the mean frequency of price change.

Why does heterogeneity in the frequency of price change amplify the degree of monetary non-neutrality? A simplifying feature of the model without intermediate inputs is that the pricing decisions of different firms are virtually independent. This is due to a combination of two features of our model. First, firms face a constant elasticity of demand, which implies that their static desired price is a constant markup over marginal costs. Second, firms' marginal costs are  $MC_t(z) = W_t/A_t(z)$  and the wage is given by  $W_t/P_t = \omega L_t^\psi C_t^\gamma = \omega C_t$ , where the second equality is due to our choice of preference parameters (see Table I). This implies that  $W_t = \omega P_t C_t = \omega S_t$  and  $MC_t(z) = \omega S_t/A_t(z)$ . So firm  $z$ 's marginal costs are exogenous and therefore independent of other firm's prices.

In this case, the degree of monetary non-neutrality in the economy is approximately a weighted average of the monetary non-neutrality in sectors viewed independently. Heterogeneity in the frequency of price change across sectors, therefore, increases the overall degree of monetary non-neutrality in the economy if the degree of monetary non-neutrality in different sectors of the economy is a convex function of each sector's frequency of price change (Jensen's inequality).

The simplest model in which to study the relationship between heterogeneity in the frequency of price change and monetary non-neutrality is the Calvo model, because in that model the firms that change their price in each period are a random sample of all firms. Carvalho (2006) shows that in the Calvo model

22. We considered models with more than fourteen sectors. They yielded results very similar to those for the fourteen-sector model.

the degree of monetary non-neutrality is highly convex in the frequency of price change. The intuition for this is simple. Consider the response to a permanent shock to nominal aggregate demand. In the Calvo model, the effect of the shock on output at any given point in time after the shock is inversely proportional to the fraction of firms that have changed their price at least once since the shock occurred. If some firms have vastly higher frequencies of price change than others, they will change their prices several times before the other firms change their prices once. But price changes after the first one for a particular firm do not affect output on average because the firm has already adjusted to the shock. Because a marginal price change is more likely to fall on a firm that has not already adjusted in a sector with a low frequency of price change, the degree of monetary non-neutrality in the Calvo model is convex in the frequency of price change.

In the menu cost model, firms are not selected at random to change their prices. The relationship between the frequency of price change and the degree of monetary non-neutrality in different sectors of the economy is therefore more complicated in a menu cost model. It depends crucially on the nature of the differences between the sectors that give rise to the differences in the frequency of price change. Consider two sectors—A and B—in the menu cost model. One reason sector A may have a lower frequency of price change than sector B is that firms in sector A may face larger menu costs than firms in sector B. Another possible reason is that firms in sector A may face smaller idiosyncratic shocks but face menu costs of the same size. These two cases will give rise to different implications regarding the relative degree of monetary non-neutrality in the two sectors.

To build intuition, it is instructive to consider the model analyzed by Caplin and Spulber (1987). They consider a continuous-time model with no idiosyncratic shocks and a process for aggregate demand that always increases. In this setting, firms raise their relative price to a level  $S$  whenever it hits a level  $s$ . If the initial distribution of relative prices is uniform, it will continue to be uniform at all future dates and money will thus be neutral for any frequency of price change. The Caplin–Spulber economy is the limiting case of our model when idiosyncratic shocks are small relative to aggregate inflation.

Figure V illustrates how the relationship between the frequency of price change and monetary non-neutrality depends critically on the relationship between the size of the menu cost

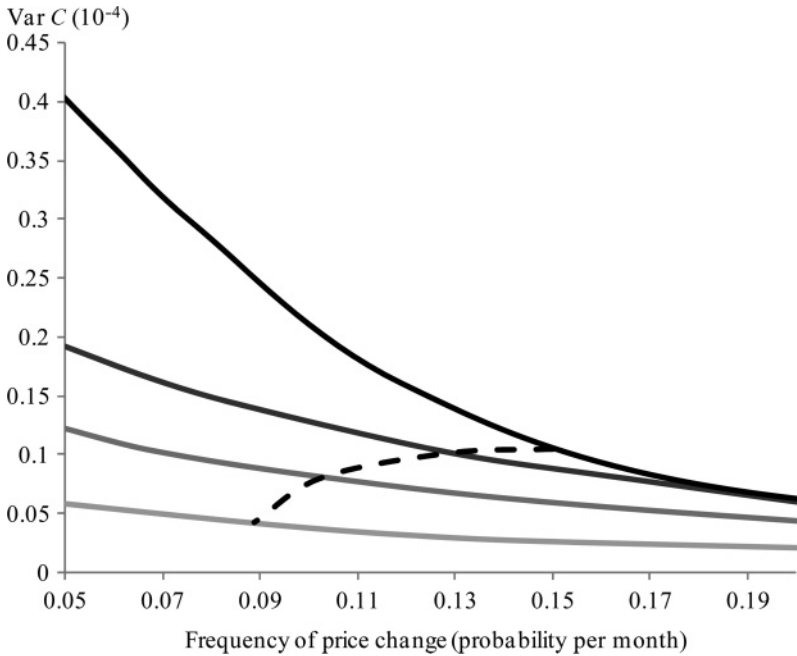


FIGURE V  
Menu Costs, Idiosyncratic Shocks, and Monetary Non-neutrality

This figure illustrates how the degree of monetary non-neutrality at a given frequency of price change depends on the size of menu costs and the size of idiosyncratic shocks. Each of the solid lines plots the degree of monetary non-neutrality in a sector for a given level of idiosyncratic shocks as the size of the menu cost changes. From top to bottom, the standard deviation of the idiosyncratic shocks ( $\sigma_\epsilon$ ) is 0.045, 0.02, 0.015, 0.01. For all the lines,  $\mu = 0.01$  and  $\sigma_\eta = 0.0037$ . The dashed line connects four sectors of a hypothetical economy in which one sector lies on each line.

and the variance of idiosyncratic shocks across the different sectors in our model. Each of the solid lines in this figure plots the degree of monetary non-neutrality in a sector for a given variance of idiosyncratic shocks as the size of the menu cost changes. The top line has the largest idiosyncratic shocks and the bottom line the smallest. For each level of the variance of idiosyncratic shocks, the frequency of price change falls and the degree of monetary non-neutrality increases as the size of menu costs increases. But the level of monetary non-neutrality at a given frequency of price change is different depending on the variance of the idiosyncratic shocks. This occurs because the “selection effect” becomes stronger as the size of the idiosyncratic shocks is reduced at a

given frequency of price change because the average inflation rate becomes a more and more important determinant of price changes relative to the idiosyncratic shocks. Intuitively, reducing the size of idiosyncratic shocks moves the economy toward the Caplin–Spulber extreme.

In actual economies, the variance of idiosyncratic shocks may vary greatly across sectors. This implies that the different sectors in a particular economy need not lie on the same line. The dashed line illustrates this by connecting four sectors of a hypothetical economy that has one sector on each line. In this example, the relationship between the size of menu costs and the variance of idiosyncratic shocks across sectors is such that the sector with the lowest frequency of price change has the lowest degree of monetary non-neutrality and the relationship between the frequency of price change and monetary non-neutrality is concave, as opposed to the convex shape of each of the solid lines. A wide range of relationships between the frequency of price change and the degree of monetary non-neutrality is possible by connecting points on different lines. Fortunately, we can empirically distinguish between the different possible cases in our model because they have different implications for the relationship between the frequency of price change and the size of price changes across different sectors of the economy.

Another determinant of the degree of amplification of monetary non-neutrality due to heterogeneity is the level of the overall frequency of price change. Table VII illustrates this using a number of simple one- and two-sector models. Holding fixed the spread between the frequency of price change in the two sectors of the two-sector economy, we raise the average frequency of price change, the degree of amplification relative to a single-sector model with the same average frequency of price change diminishes. Specifically, the first row presents results for a two-sector economy in which half of firms have a frequency of price change of 10% and the other half have a frequency of price change of 20%. This economy is compared to a single-sector economy with a frequency of price change of 15%. The two-sector economy yields 14% more monetary non-neutrality. Rows (2) through (4) show that the degree of amplification falls steeply for similar comparisons as the overall frequency of price change rises. A comparison of rows (1), (5), and (6) shows that amplification arises from heterogeneity in the frequency of price change across sectors, not other features such as its skewness.

TABLE VII  
AMPLIFICATION DUE TO HETEROGENEITY

	Two-sector models			One-sector models		Amp. factor
	Freq. 1	Freq. 2	Var( $C_t$ )	Freq.	Var( $C_t$ )	
(1)	0.10	0.20	0.1194	0.15	0.1050	1.137
(2)	0.20	0.30	0.0395	0.25	0.0360	1.098
(3)	0.30	0.40	0.0154	0.35	0.0152	1.014
(4)	0.40	0.50	0.0060	0.45	0.0059	1.010
(5)	0.10	0.30	0.0889	0.20	0.0620	1.433
(6)	0.10	0.40	0.0702	0.25	0.0360	1.949

*Notes.* The table compares monetary non-neutrality in two-sector models to the value in one-sector models with the same average frequency of price change. Each row in the table presents a two-sector model in which the two sectors have different frequencies of price change and a one-sector model with a frequency of price change equal to the average frequency of price change in the two-sector model. “Freq 1” denotes the frequency of price change in Sector 1 of the two-sector model. “Freq 2” denotes the frequency of price change in the other sector. “Freq” denotes the frequency of price change in the one-sector model. “Var( $C_t$ )” denotes the variance of output multiplied by  $10^4$ . “Amp. factor” denotes the factor by which monetary non-neutrality is higher in the two-sector model than in the one-sector model.

Now that we have established what *can* happen in the model, let us consider what *does* happen for parameter values calibrated to U.S. data. The darker line in Figure VI plots the variance of real output as a function of the frequency of price change for our calibration of the U.S. economy. It shows that the relationship between the degree of monetary non-neutrality and the frequency of price change in our model is highly convex. This yields the large amount of amplification documented in Table VI. The convexity in our baseline calibration is a consequence of three features of the U.S. data: (1) the low average level of inflation in the U.S. economy, (2) the fact that the average size of price changes is large and that there is no strong correlation between the size and frequency of price change across sectors, and (3) the relatively low average frequency of price change in the U.S. economy. The lighter line in Figure VI plots a counterfactual calibration of our model in which we have assumed that the yearly inflation rate in the U.S. is 12% rather than 3.5% and the variance of the idiosyncratic shocks that affect firm’s marginal costs is roughly four times smaller than in our baseline calibration. In this case, the relationship between the degree of monetary non-neutrality and the frequency of price change is almost linear and heterogeneity implies little amplification of monetary non-neutrality.

Our baseline model assumes that nominal output follows a random walk with drift. Empirically, the growth rate of U.S.

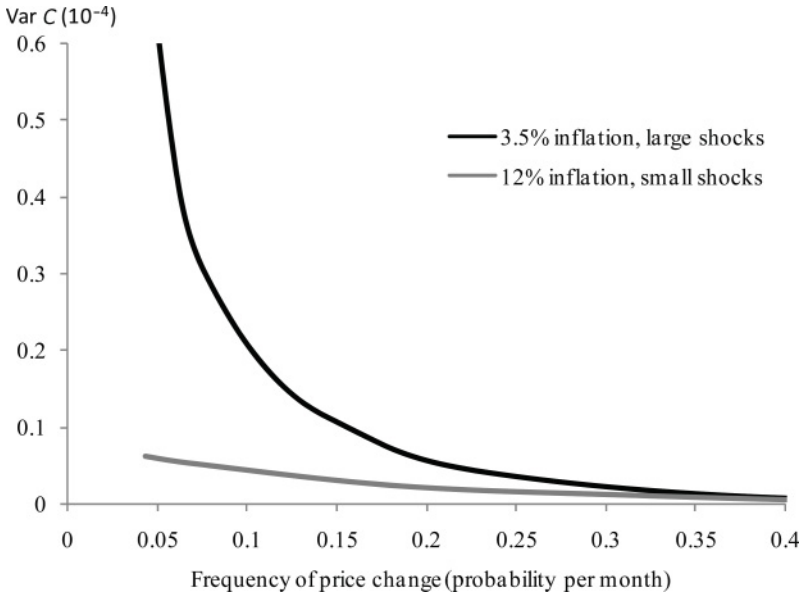


FIGURE VI

## Variance of Output as a Function of the Frequency of Price Change

This figure plots the variance of value-added output as a function of the frequency of price change as we vary the menu cost for two calibrations of our menu-cost model without intermediate inputs. First, we present our benchmark calibration of  $\mu = 0.0028$ ,  $\sigma_\eta = 0.0065$ , and  $\sigma_\varepsilon = 0.0425$  (dark line). Second, we present a calibration in which  $\mu = 0.01$ ,  $\sigma_\eta = 0.0065$ , and  $\sigma_\varepsilon = 0.01$  (light line).

nominal GDP over the period 1947–2005 is better described as an AR(1) with an autoregressive coefficient of roughly 0.5 at a quarterly frequency. For robustness, we have solved a version of our model in which nominal output growth follows an AR(1) calibrated to the data.<sup>23</sup> The model with AR(1) growth in nominal output yields somewhat higher monetary non-neutrality than the baseline model.

The limited effect of persistence in nominal output growth in our model is consistent with earlier work by Midrigan (2006). As Midrigan (2006) emphasizes, the effects of persistence in the money growth process are quite different in the menu cost model from those in the Calvo model. In the menu cost model, firms may

23. We choose the autocorrelation and innovation variance for monthly nominal output growth in such a way that the resulting process—when time-aggregated to a quarterly frequency—has the same autocorrelation and unconditional variance as quarterly nominal GDP growth in the data.



optimally delay price changes after they see a shock to nominal output in anticipation of further movements in the same direction in the near future. This desire to optimally time price changes may lead to a wider inaction region for prices in the AR(1) case than the random walk case. In the Calvo model, firms are not able to time their price changes. Those firms that have an opportunity to change their prices immediately after a persistent shock respond preemptively to future expected movements in nominal output because they can't know when they will again get to change their prices, raising the responsiveness of prices. Midrigan (2006) notes that firms with state-dependent pricing policies do not have the same incentive to front-load because they are able to choose the timing of their next price adjustments after a shock.

To evaluate the sensitivity of our results to the introduction of time-dependent price changes we consider simulations of the CalvoPlus model introduced in Section II.C. Recall that in the CalvoPlus model firms always have the option to change their prices at a relatively high cost but also sometimes receive the opportunity to change their prices at a lower cost. Figure VII plots the variance of output in a single-sector version of the CalvoPlus model as the fraction of price changes the firm makes in the low-menu cost state varies from zero to one.<sup>24</sup> The figure shows that the degree of monetary non-neutrality drops off rapidly as the fraction of price changes in the low-cost state falls below 100%. When 85% of price changes occur in the low-menu cost state, the variance of output is less than half of what it is when all price changes occur in the low-cost state. When 50% of price changes occur in the low-menu cost state, the variance of output is close to identical to the value in the constant-menu cost model. Figure VII therefore suggests that the relatively large amount of monetary non-neutrality generated by the Calvo model is quite sensitive to even a modest amount of selection by firms regarding the timing of price changes.

Although the overall level of monetary non-neutrality is much higher in the CalvoPlus model than in the pure menu cost model, the degree of amplification due to heterogeneity is very similar. To illustrate this, we consider results for the CalvoPlus model calibrated so that roughly 75% of price changes occur in the

24. In this experiment, we set  $1 - \alpha$  equal to the median frequency of price change in the economy and  $\sigma_\epsilon = 0.0425$ . We vary  $\chi_h$  and  $\chi_l$  so that the model matches the median frequency of price changes and a particular fraction of price changes in the low-menu cost state.

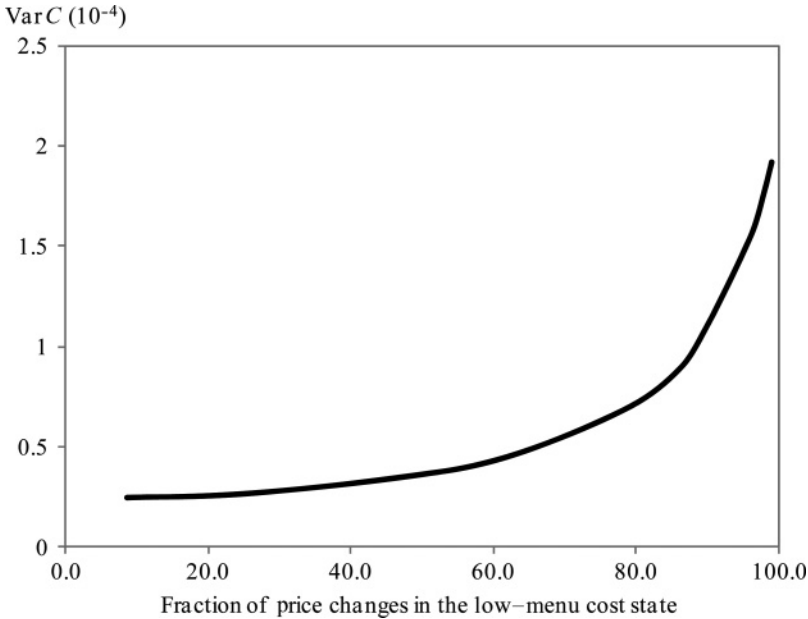


FIGURE VII  
Monetary Non-neutrality in the CalvoPlus Model

This figure presents the variance of value-added output in the single-sector CalvoPlus model without intermediate inputs as a function of the fraction of price changes in the low-menu cost state. The variance of the idiosyncratic shocks is fixed at  $\sigma_\varepsilon = 0.0425$  (the same value as in the single-sector menu cost model without intermediate goods). The menu costs in the high- and low-menu cost states are calibrated to match the weighted median frequency of price change 8.7%. The fraction of time spent in the low-cost state  $1 - \alpha = 8.7\%$ .

low-menu cost state in the third column of Table VI.<sup>25</sup> The overall level of monetary non-neutrality is about three times higher in this calibration of the CalvoPlus model. However, the degree of amplification due to heterogeneity is very similar to what it is in the pure menu cost model. In both cases, allowing heterogeneity in the frequency of price change roughly triples the degree of monetary non-neutrality. Similar qualitative results hold for other calibrations of the CalvoPlus model.

25. In parameterizing the CalvoPlus model, we must set values for frequency of low-cost repricing opportunities ( $1 - \alpha$ ) as well as the menu costs in the low- and high-cost states ( $\chi_l$  and  $\chi_h$ ). A simple choice would be to set  $\chi_l = 0$  as in the Calvo model. However, this calibration strategy yields an unrealistically small size of price changes. We therefore set,  $\chi_l = \chi_h/40$ . We set  $1 - \alpha$  equal to the frequency of price change in each sector and choose  $\chi_h$  and  $\sigma_\varepsilon$  to match the frequency and size of price changes in each sector. This parameterization implies that roughly 75% of price changes occur in the low-menu cost state.

TABLE VIII  
INTERMEDIATE INPUTS AND MONETARY NON-NEUTRALITY

	Interm. input share	Frequency of price change	
		21.1%	8.7%
	Monetary non-neutrality: $\text{Var}(C_t)$		
(1)	0.00	0.055	0.261
(2)	0.50	0.109	0.443
(3)	0.60	0.133	0.518
(4)	0.70	0.182	0.658
(5)	0.80	0.276	0.844
(6)	0.90	0.471	1.346

*Notes.* This table presents estimates of the variance or real value-added output for a single-sector version of the menu cost model for a range of values of the intermediate input share,  $s_m$ . In all cases, the model is calibrated to match the median size of price changes of 8.5%. In the first column, the model is calibrated to match the weighted mean frequency of price change of 21.1%, whereas in the second column, it is parameterized to match the weighted median frequency of price change of 8.7%.

## V. INTERMEDIATE INPUTS AND MONETARY NON-NEUTRALITY

### V.A. *Intermediate Inputs as a Source of Amplification*

We now incorporate intermediate inputs into the model. In Section III, we argue that an empirically plausible level for the intermediate input share is 0.7. The second column of Table VI presents results for the menu cost model with this intermediate inputs share. This calibration yields roughly triple the amount of monetary non-neutrality that the model without intermediate inputs does. Table VIII presents results for several additional values of the intermediate inputs share.

As is well known, the presence of intermediate inputs amplifies the degree of monetary non-neutrality because it causes the pricing decisions of firms in the model to become strategic complements.<sup>26</sup> In the model with intermediate inputs, firm's marginal costs are a weighted average of the wage the firm faces and the cost of its inputs. Specifically, the firm's marginal costs

26. This point was first made by Basu (1995). Important additional contributions have been made by Huang and Liu (2004) and Huang (2006). Huang and Liu (2004) show that intermediate inputs increase the persistence of output in response to monetary shocks in the presence of staggered prices but not in the presence of staggered wages. Huang (2006) studies a model with both intermediate inputs and specific factors and argues that the presence of these two factors together generates a negative interaction effect that weakens the degree of strategic complementarity.

are given by

$$MC_t(z) = \frac{W_t^{1-s_m} P_t^{s_m}}{A_t(z)} = \frac{\omega S_t^{1-s_m} P_t^{s_m}}{A_t(z)},$$

where the later equality follows from the definition of  $S_t$  and the fact that  $W_t/P_t = \omega L_t^\psi C_t^\gamma = \omega C_t$  given our calibration of  $\psi = 0$  and  $\gamma = 1$ . Because the prices of the firm's inputs are the prices of the other goods in the economy, the firm's marginal costs depend directly on the prices of the other goods in the economy. This is the source of strategic complementarity in the model with intermediate inputs. Because the prices of other goods in the economy respond sluggishly to an increase in  $S_t$  when firms face menu costs, the firm's marginal costs rise by less than 1% in response to a 1% increase in  $S_t$  when  $s_m > 0$ . As a consequence, firms that change their price soon after a shock to  $S_t$  choose a lower price than they would if labor was their only input. In other words, firms choose not to change their prices as much as they otherwise would because the price of many of their inputs have not yet responded to the shock.<sup>27</sup>

An important qualitative difference between our menu cost model and time-dependent models is the way in which heterogeneity in the frequency of price change and intermediate inputs interact. In our menu cost model, the amplification of monetary non-neutrality due to intermediate inputs is virtually identical in the multisector model to that in the single-sector model. In other words, these two sources of amplification are roughly independent of each other. In contrast, Carvalho (2006) emphasizes the importance of the interaction between these two features in models with time-dependent price changes. Our CalvoPlus model confirms this interaction. In the Calvo model with strategic complementarity and heterogeneity in the frequency of price change, the firms in sectors with high frequency of price change are influenced by the nonresponse of firms in the low frequency of price change sectors. However, firms in the sectors with low frequency of price change are much less influenced by firms in the sectors with high frequency of price change because so many of them

27. The firm's profit function in our model simply implies that a fraction  $1 - s_m$  of costs are proportional to  $S_t$ , whereas a fraction  $s_m$  are proportional to  $P_t$ . In the derivation of this equation, we assume that the "flexible" input is labor and the "sluggish" input is intermediate inputs. However, this profit function is consistent with other models in which, for example, wages are sluggish (Burstein and Hellwig 2006) and other inputs are flexible.

don't respond at all. In the language of Haltiwanger and Waldman (1991), the firms with a high frequency of price change are "responders," whereas most of the firms with a low frequency of price change are exogenously determined to be "nonresponders." This asymmetry implies that the equilibrium increasingly becomes disproportionately affected by the sectors with low frequency of price change as the degree of strategic complementarity increases. In the Calvo model, there is thus an interaction between strategic complementarity and heterogeneity in the frequency of price change, as in Haltiwanger and Waldman (1991).

In contrast, in the menu cost model, the extensive margin of price change allows the firms with low frequency of price change to be influenced by the presence of firms with high frequency of price change firms to a much greater extent than in the Calvo model. In particular, when a shock occurs, some firms that would otherwise not have changed their prices do change their prices because firms in the sector with high frequency of price change are changing their prices. This implies that there is not as sharp a distinction between responders and nonresponders, and mutes the interaction between strategic complementarity and heterogeneity in the frequency of price change.

How does the degree of real rigidity in our model compare to the degree of real rigidity in recent quantitative monetary business cycle models such as those of Christiano, Eichenbaum, and Evans (2005) and Smets and Wouters (2007)? The relative volatility of marginal costs and output is a measure of ( $\Omega$ -type) real rigidity both in our model and in these other models. We can directly compare the degree of real rigidity in our model to that in these other models by calculating the relative standard deviation of marginal costs and output in our model and comparing it to this same statistic in a quantitative DSGE model. Justiniano and Primiceri (2008b) analyze a state-of-the-art quantitative DSGE model that builds heavily on the models of Christiano, Eichenbaum, and Evans (2005) and Smets and Wouters (2007). In their model, the standard deviation of marginal costs relative to output is 0.36.<sup>28</sup> In our model, this statistic is equal to  $s_m$ , which is 0.3 in our baseline calibration with intermediate inputs. Thus, our calibration implies a degree of real rigidity very similar to the degree of real rigidity estimated by Justiniano and Primiceri

28. We thank Alejandro Justiniano and Giorgio Primiceri for producing this statistic for us. This statistic is for the time-invariant version of their model.

(2008b). Were we to calibrate  $s_m = 0.64$ , our model would have exactly the same amount of real rigidity as theirs. This change of calibration would not materially affect our results.

The model we consider above makes the simplifying assumption that  $s_m$  is the same for all sectors and also that all sectors use the same mix of intermediate inputs. We have analyzed an extension where we allow  $s_m$  to differ across sectors. We set the sectoral  $s_m$  based on data from the U.S. Input–Output data for 2002 presented in Table IV. Qualitatively, allowing for this type of heterogeneity affects our results through two channels. First, the degree of monetary non-neutrality in a sector is a convex function of  $s_m$ , other things equal. Jensen’s inequality thus implies that an economy with heterogeneous  $s_m$  will have more monetary non-neutrality than an economy in which all sectors have the average  $s_m$ . Second, the degree of amplification due to heterogeneity is affected by the correlation between  $s_m$  and the frequency of price change across sectors. Empirically,  $s_m$  in a sector is positively correlated with the frequency of price change in the sector. This leads to further amplification of monetary non-neutrality because the price level in relatively flexible sectors is held back by heavy use of intermediate inputs from sticky sectors. Quantitatively, extending our model to allow for heterogeneity in  $s_m$  across sectors raises the degree of monetary non-neutrality, but the magnitude of the effect is quite small.

It is much harder computationally to allow different sectors to use different mixes of intermediate inputs in our menu cost model because this would imply that the inflation rates of all fourteen sectors would be state variables in the model. However, Bouakez, Cardia, and Ruge-Murcia (2009a) carefully analyze these issues in the context of the multisector Calvo model. They incorporate detailed evidence on sectoral input–output tables into a multisector Calvo model and find that the amplification of monetary non-neutrality associated with sectoral heterogeneity carries over to this more general environment.

### *V.B. A Comparison with Other Sources of Strategic Complementarity*

Strategic complementarity has long been an important source of amplification of nominal rigidities (Ball and Romer 1990; Woodford 2003). However, recent work has cast doubt on strategic complementarity as a source of amplification in menu cost models with

idiosyncratic shocks by showing that the introduction of strategic complementarity can make it difficult to match the large observed size of price changes for plausible values of the menu cost and the variance of the idiosyncratic shocks. Klenow and Willis (2006) show that a model with demand-side strategic complementarity of the type emphasized by Kimball (1995) requires massive idiosyncratic shocks and implausibly large menu costs to match the size of price changes observed in the data. Golosov and Lucas (2007) note that their model generates price changes that are much smaller than those observed in the data when they consider a production function with diminishing returns to scale due to a fixed factor of production. Burstein and Hellwig (2006) use supermarket scanner data to calibrate a model with a fixed factor of production and both demand and supply shocks. They find that even with large demand shocks, a substantial amount of strategic complementarity requires large menu costs to match the micro-data on the size of price changes.

The challenge first emphasized by Klenow and Willis (2006) that commonly used sources of monetary non-neutrality cannot match the size of price changes for reasonable parameter values is a serious one, given the extent to which many monetary business cycle models rely on these mechanisms to amplify monetary non-neutrality. However, it is not clear from Klenow and Willis (2006) what the scope of this problem is. Does it apply to all sources of strategic complementarity or just some? If it only applies to some, to which ones does it apply? The goal of this section is to clarify this issue.

Strategic complementarity generated by firms' use of intermediate inputs does not affect the size of price changes or require unrealistically large menu costs and idiosyncratic shocks (see Table III). The reason for this difference can be illustrated using a dichotomy developed by Ball and Romer (1990) and Kimball (1995). A firm's period- $t$  profit function may be written as  $\Pi(p_t/P_t, S_t/P_t, \tilde{A}_t)$ , where  $p_t/P_t$  is the firm's relative price,  $S_t/P_t$  denotes real aggregate demand, and  $\tilde{A}_t$  denotes a vector of all other variables that enter the firm's period- $t$  profit function. The firm's desired price under flexible prices is then given by  $\Pi_1(p_t/P_t, S_t/P_t, \tilde{A}_t) = 0$ , where the subscript on the function  $\Pi$  denotes a partial derivative. Notice that

$$(17) \quad \frac{\partial p_t}{\partial P_t} = 1 + \frac{\Pi_{12}}{\Pi_{11}}.$$

Pricing decisions are strategic complements if  $\zeta = -\Pi_{12}/\Pi_{11} < 1$  and strategic substitutes otherwise.<sup>29</sup> Following Ball and Romer (1990), we can divide mechanisms for generating strategic complementarity into two classes: (1) those that raise  $-\Pi_{11}$  and (2) those that lower  $\Pi_{12}$ . We refer to these two classes as  $\omega$ -type strategic complementarity and  $\Omega$ -type strategic complementarity, respectively.<sup>30</sup> Mechanisms that generate  $\omega$ -type strategic complementarity include nonisoelastic demand and fixed factors of production. Mechanisms that generate  $\Omega$ -type strategic complementarity include real wage rigidity and sticky intermediate inputs. Notice that  $\partial p_t / \partial \tilde{A}_t = -\Pi_{13} / \Pi_{11}$ . This implies that  $\omega$ -type strategic complementarity mutes the response of the firm's desired price to other variables such as idiosyncratic shocks, whereas  $\Omega$ -type strategic complementarity does not. Models with a large amount of  $\omega$ -type strategic complementarity therefore have trouble matching the large size of price changes seen in the microdata, whereas this problem does not arise in models with a large amount of  $\Omega$ -type strategic complementarity.

The key difference between the two types of strategic complementarity is that strategic complementarity due to intermediate inputs affects only the firm's response to aggregate shocks, whereas strategic complementarity due to a fixed factor or nonisoelastic demand mutes the firm's response to both aggregate shocks and idiosyncratic shocks. In the model with a fixed factor, the firm's marginal product of labor increases as its level of production falls. The firm's marginal costs therefore fall as it raises its price in response to a fall in productivity, because a higher price leads to lower demand. This endogenous feedback of the firm's price on its marginal costs counteracts the original effect that the fall in productivity had on marginal costs and leads the firm's desired price to rise by less than it otherwise would. In the model with intermediate inputs, the firm's marginal cost is not affected by its own pricing decision. The strategic complementarity in the model with intermediate inputs arises because of the rigidity of other firms' prices rather than because of endogenous feedback on marginal costs from the firm's own pricing decision.

Gertler and Leahy (2008) explore an alternative menu cost model with strategic complementarity that does not affect the size of price changes. Their model has sector-specific labor markets in

29. At the equilibrium  $\Pi_{11} < 0$  and  $\Pi_{12} > 0$ .

30. These names are based on the notation used by Kimball (1995).



which firms receive periodic idiosyncratic shocks. They assume that in each period firms in only a fraction of sectors receive idiosyncratic shocks and change their prices. This staggering of price changes across sectors generates strategic complementarity that amplifies the monetary non-neutrality in their model. The fact that the labor market is segmented at the sectoral level rather than the firm level avoids endogenous feedback on marginal costs from the firms' own pricing decisions and allows their model to match the size of price changes without resorting to large shocks or large menu costs.

The Gertler–Leahy model assumes that in each period there are entire sectors in which no firm changes prices and other sectors in which a large fraction of firms change prices. Time series data on the evolution of the frequency of price change in different sectors of the U.S. economy do not support the notion that the frequency of price change within narrowly defined categories varies greatly from month to month, even within city. In principle, a similar effect arises if one assumes only that the frequency of price change varies across sectors. We have simulated a six-sector menu cost model with sector-specific labor markets in which the frequency and size of price change is calibrated to match the mean of these statistics in different sectors of the U.S. economy. This model does not generate a quantitatively significant degree of strategic complementarity.

### *V.C. Intermediate Inputs and Sectoral Comovement*

We have emphasized the importance of intermediate inputs in amplifying the monetary non-neutrality generated by nominal rigidities. Another important advantage of the model with intermediate inputs is its more realistic implications for the behavior of sectoral output. The relatively modest response of aggregate value-added output to aggregate demand shocks in the model without intermediate inputs masks much larger responses of output in individual sectors. Figure VIII plots the response of aggregate output and sectoral output to an expansionary demand shock in our fourteen-sector model without intermediate inputs. The sectoral responses vary greatly. Output in the sectors with greatest price rigidity rises by several times as much as aggregate output, whereas output in the sectors with most price flexibility falls sharply. Figure IX is the corresponding plot for the model with intermediate inputs. In contrast to the model without intermediate inputs, output in all sectors rises sharply in response

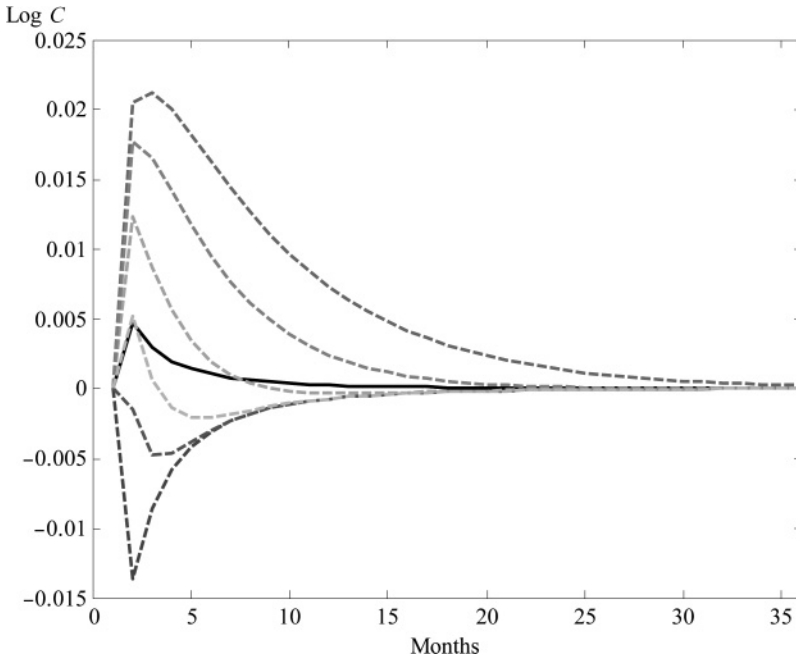


FIGURE VIII

Response of Aggregate Output and Sectoral Output without Intermediate Inputs

This figure plots the response of aggregate real value-added output (solid line) and sectoral output for several sectors of the fourteen-sector model without intermediate inputs to a 1% permanent increase in nominal aggregate demand. From top to bottom the sectors that are plotted are services (group 5), apparel, services (group 3), transportation goods, utilities and vehicle fuel, and used cars.

to an expansionary demand shock and the differences between sectors are relatively modest.

In the model without intermediate inputs, the desired price of all firms rises approximately one for one in percentage terms with nominal aggregate demand and is approximately independent of the prices charged by other firms. As a consequence, the sectoral price index in sectors with a high frequency of price change—such as gasoline—quickly rises proportionally to the shock, whereas the sectoral price index in sectors with more rigid prices adjusts more slowly. This causes a large change in relative prices across sectors which leads consumers to shift expenditures toward the sectors in which prices are lower (the sticky price sectors).<sup>31</sup> In

31. It is easy to show that aggregate productivity shocks lead to similar lack of comovement across sectors.

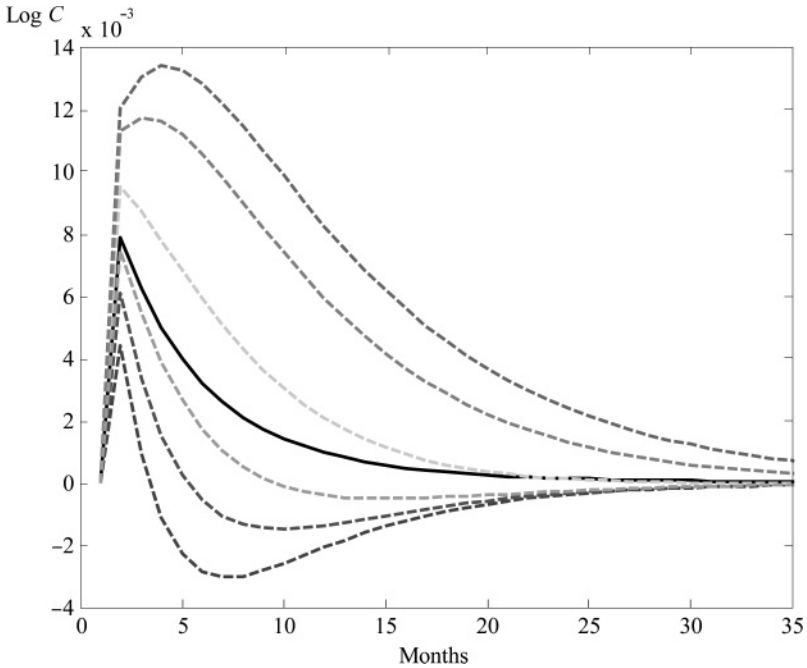


FIGURE IX

Response of Aggregate Output and Sectoral Output with Intermediate Inputs

This figure plots the response of aggregate real value-added output (solid line) and sectoral output for several sectors of the fourteen-sector model with intermediate inputs to a 1% permanent increase in nominal aggregate demand. From top to bottom the sectors that are plotted are services (group 5), apparel, services (group 3), transportation goods, utilities and vehicle fuel, and used cars.

contrast, in the model with intermediate goods, a firm's desired price is heavily dependent on the prices of other firms. This implies that even the flexible price firms don't react strongly to the shock and relative price differences are much smaller.

A key characteristic of business cycles is that virtually all sectors of the economy comove strongly (Lucas 1977; Stock and Watson 1999). The lack of comovement across sectors in the model without intermediate inputs is therefore grossly at odds with the data. This lack of comovement across sectors in models with heterogeneity in the degree of price flexibility has been noted and analyzed by several recent papers including Bills, Klenow, and Kryvtsov (2003), Carlstrom and Fuerst (2006), and Barsky, House, and Kimball (2007). The analysis above shows that allowing for intermediate goods substantially increases the comovement

between different sectors of the economy.<sup>32</sup> This result also holds in our extended model with heterogeneity in intermediate input use.<sup>33</sup>

## VI. EXTENDING THE MODEL TO INCORPORATE PRODUCT TURNOVER

The baseline model we have adopted in this paper is one in which price rigidity arises because firms face a fixed cost of changing their prices. In this setting, firms optimally choose the timing of price changes as well as the new price they set. We have identified regular price changes in the data as price changes that are timed optimally by firms. In this section, we argue that—in addition to always having the option of incurring a fixed cost to change their price—firms may also receive occasional opportunities to change their prices at comparatively low-cost. The Calvo-Plus model we introduce in Section II.C captures this possibility. These additional low-cost price changes will affect the degree of price flexibility in the economy. However, because their timing is not chosen optimally, they will induce less price flexibility than the same number of regular price changes.

An important example of instances in which firms may receive opportunities to change their prices at low cost is the times at which firms introduce new products. Product turnover is quite rapid in certain sectors of the economy. And when a firm introduces a new product, it must necessarily set a new price for this product. Rapid product turnover can therefore affect the degree of price flexibility in the economy. Furthermore, because firms can often anticipate future product turnover—such as, fall–spring

32. Hornstein and Praschnik (1997), Dupor (1999), and Horvath (2000) discuss the effects of input–output linkages for comovement in a real–business cycle framework. Barsky, House, and Kimball (2007) also discuss a number of other mechanisms for ameliorating this “comovement problem.”

33. Bills, Klenow, and Kryvtsov (2003) argue that the relative prices of goods in sectors with flexible prices do not increase after an expansionary monetary policy shock as the sticky-price business cycle model implies they should. Boivin, Giannoni, and Mihov (2009) point out that the empirical model used by Bills, Klenow, and Kryvtsov (2003) gives rise to a substantial “price-puzzle” in response to monetary shocks with inflation falling for several quarters after an expansionary shock. Boivin, Giannoni, and Mihov (2009) argue that this suggests misspecification of the monetary shocks. They analyze the behavior of sectoral output after a monetary shock in a factor-augmented vector autoregression model that does not give rise to a price puzzle and show that their estimated response of prices in sticky vs. flexible price sectors lines up well with the sticky-price model. Using a different empirical strategy, Mackowiak, Moench, and Wiederholt (2009) find that prices in flexible-price sectors respond more rapidly to aggregate shocks than prices in sticky-price sectors. Bouakez, Cardia, and Ruge-Murcia (2009a) provide further evidence that sectors with more frequent price changes respond more rapidly to monetary policy shocks using a structural estimation approach.

turnover in apparel—they may decide not to incur the fixed cost needed to change the price of an existing product.

Table II reports the frequency of product substitution for the sectors in our multisector models. It reveals that product substitution is a frequent occurrence in several categories of durable goods—apparel, transportation goods (cars), household furnishings, and recreation goods—but less frequent for other products. A number of these categories—especially apparel—have a very low frequency of price change but a substantial frequency of product turnover.

Many factors influence a firm's decision about the timing of new product introduction including seasonality, development cycles, innovation, and random shifts in consumer tastes. Figure X plots the frequency of product substitution across different months of the year for the four categories for which product substitution is most frequent. In apparel, seasonal variation in tastes is a dominant factor in the timing of product introduction. The main determinant of the timing of product entry and exit is the timing of the fall and spring clothing seasons. In the automobile industry, product introduction is heavily influenced by a yearly development cycle with new models being introduced in the fall of each year.

This evidence suggests that in these product categories—where product turnover is relatively important—the timing of product turnover may be largely orthogonal to a firm's desire to change its price and to macroeconomic conditions. Earlier in the paper, we have used the CalvoPlus model as a time-dependent benchmark. We can also use it to assess the robustness of our results to the introduction of product turnover.

A computationally tractable way of modeling product turnover is to consider a model in which new products arrive according to an exogenous Poisson process. This model is equivalent to the CalvoPlus model where price changes are free in the low-cost state ( $\chi_l = 0$ ) and the probability of receiving an opportunity to change prices for free ( $1 - \alpha$ ) is equal to the frequency of product substitution in each sector.<sup>34</sup> In this calibration of the CalvoPlus

34. One could also consider a "TaylorPlus" model, that is, a model in which product introduction is on a fixed schedule as in Taylor (1980). Such a TaylorPlus model is much less tractable computationally because the months of the year are state variables in that model. The CalvoPlus and TaylorPlus models both imply that the timing of product introductions is not driven by the firm's desire to change prices. In both models, such price changes would thus not exhibit a "selection" effect.

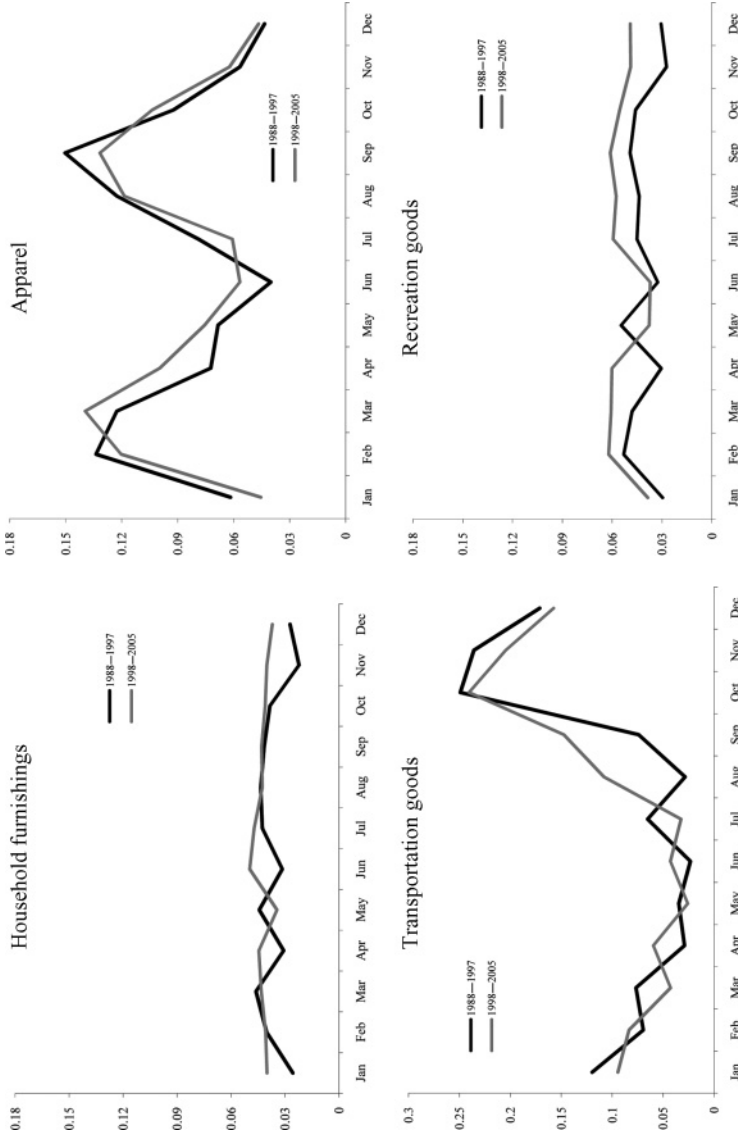


FIGURE X  
Seasonality in Product Substitution

TABLE IX  
MULTISECTOR MODELS WITH PRODUCT FLEXIBILITY

	Menu cost		CalvoPlus subs.		Menu cost subs.	
	$s_m = 0$	$s_m = 0.7$	$s_m = 0$	$s_m = 0.7$	$s_m = 0$	$s_m = 0.7$
Monetary non-neutrality: $\text{Var}(C_t)$						
One-sector model (mean)	0.055	0.182	0.173	0.461	0.036	0.157
Six-sector model	0.136	0.470	0.458	1.492	0.092	0.332
Nine-sector model	0.143	0.576	0.495	1.563	0.104	0.412
Fourteen-sector model	0.188	0.627	0.520	1.709	0.111	0.410

*Notes.* This table presents estimates of the variance of real value-added output for alternative calibrations of our multisector model to evaluate the effect of introducing product turnover as a source of price flexibility. The variance of real value added output is multiplied by  $10^4$ . The first two columns present results for the baseline menu cost model calibrated to match the frequency of price change across sectors. The third and fourth columns present results for the CalvoPlus model where product introductions are viewed as “low-cost” price changes, whereas price changes for identical items are treated “high-cost” price changes. In this model, the cost of low-cost price changes is  $\lambda_l = 0$  and the frequency of such price changes is  $1 - \alpha = \text{freq. of substitutions}$ , whereas  $\lambda_h$  is calibrated so that that frequency of price change in the high-cost state equals the frequency of price change for identical items in the data. The fifth and sixth columns present results for the menu cost model calibrated to match the frequency of price change plus substitutions.

model, the menu cost in the high-cost state is set so that the frequency of high-cost price changes in the model matches the frequency of price changes for identical items in the data for each sector. In other words, all price changes for identical items are viewed as state-dependent as in our baseline menu cost model. However, now we consider an additional dimension of flexibility in the form of price changes due to product turnover.<sup>35</sup>

Table IX shows that product turnover associated with factors unrelated to the firms’ pricing decisions have little effect on the monetary non-neutrality implied by the model. This is because the “selection effect” applies only to the regular price changes. Although new fashion items are priced to keep up with inflation, they are not (in this model) introduced *because* the old fashion items were mispriced. For comparison purposes, Table IX also presents results for a calibration of the menu cost model where we treat product introductions as if they were the

35. Broda and Weinstein (2007) argue that product introduction is procyclical. However, the variation in product turnover at business cycle frequencies is an order of magnitude smaller than the seasonality we document in Figure X. Our model could easily be extended to consider intermediate cases where the timing of some product introductions but not others is exogenous to the firm’s desire to change prices.

TABLE X  
NOMINAL RIGIDITIES AND THE BUSINESS CYCLE

	Var( $C_t$ ) ( $10^{-4}$ )	Frac. tot. (%)
HP-filtered U.S. GDP 1947–2005	2.72	100
Multisector model with $s_m = 0.7$	0.63	23
Multisector model with $s_m = 0$	0.19	7
Single-sector model with $s_m = 0.7$	0.18	7
Single-sector model with $s_m = 0$	0.05	2

*Notes.* This table reports the variance of HP-filtered U.S. real GDP for 1947–2005 as well as estimates of the variance of real value-added output for the single-sector and fourteen-sector versions of our menu cost model for two values of the intermediate input share ( $s_m$ ). It also reports the fraction of the variance of HP-filtered U.S. real GDP accounted for by each of these models.

same as regular price changes. In this case, “product flexibility” would have a much larger effect on monetary non-neutrality. In either case, the inclusion of product substitutions in the model has little effect on the amplification effect associated with heterogeneity.

## VII. DO MENU COSTS GENERATE SIZABLE MONETARY NON-NEUTRALITY?

In the context of a simple menu cost model, Golosov and Lucas (2007) argue that the amount of monetary non-neutrality generated by nominal rigidities is “small and transient.” An important question is whether this conclusion holds up in a richer, more realistic setting. To answer this question, we compare the variance of real output generated by our multisector model with intermediate inputs in response to calibrated aggregate nominal shocks to the variance of Hodrick–Prescott (HP)-filtered log U.S. real GDP (Hodrick and Prescott 1997).

Table X reports the results of this comparison. The variance of HP-filtered log U.S. real GDP for the period 1947–2006 is  $2.72 \times 10^{-4}$ . The menu cost model is simulated with nominal aggregate shocks that are calibrated as described in Section III to match the behavior of log U.S. nominal GDP over the period 1947–2005, less the growth rate of log real GDP. The variance of real output in response to these nominal aggregate shocks in our multisector model with intermediate inputs is  $0.63 \times 10^{-4}$ . Our model is therefore able to account for 23% of the U.S. business cycle. This result of our model accords well with empirical evidence



on the importance of nominal shocks for business cycle fluctuations. Lucas (2003) argues that the shocks that Shapiro and Watson (1988) refer to as “demand” shocks should be interpreted as “nominal” shocks. These shocks capture not only the effect of monetary disturbances but also temporary monetary non-neutrality due to real shocks. Shapiro and Watson (1988) attribute 28% of the variation in output at short horizons to these nominal shocks. In contrast, a single-sector version of our model without intermediate inputs—a model that is virtually identical to the Golosov and Lucas (2007) model—yields variation in real output that can account for only 2% of the U.S. business cycle.<sup>36</sup>

Our model does not incorporate aggregate real shocks. It is therefore not able to match the behavior of real output. The absence of aggregate real shocks in our model also means that we must abstract from any relationship between real shocks and movements in nominal aggregate demand. In a richer model with both real and nominal aggregate shocks, it would be possible to allow nominal aggregate demand to respond both to real shocks and nominal shocks. It would then be possible to “turn off” the nominal shocks and assess how large a fraction of business cycle fluctuations in output they cause. This type of exercise would arguably yield a preferable estimate of the importance of monetary non-neutrality in business cycle dynamics to the one we present above. Carrying out this exercise is, however, beyond the scope of this paper.

## VIII. CONCLUSIONS

Recent work on state-dependent pricing models suggests that these models generate only a “small and transient” amount of monetary non-neutrality (Golosov and Lucas 2007). Given the importance of nominal rigidities as a source of monetary non-neutrality in most monetary models, this conclusion poses a serious challenge for monetary economics. We extend a simple benchmark menu cost model to include two features for which there exists particularly clear empirical evidence: (1) heterogeneity across sectors in the frequency and size of price changes and (2) intermediate inputs. We show that when we subject our

36. Midrigan (2006) identifies two other mechanisms that raise the degree of monetary non-neutrality in a menu cost model: fat-tailed idiosyncratic shocks and multiproduct firms with scale economies in changing prices.

model to calibrated nominal shocks it generates fluctuations in real output that can account for 23% of the U.S. business cycle. This accords well with Shapiro and Watson's (1988) result that 28% of variation in output at short horizons is due to nominal shocks.

Our multisector model generates three times as much monetary non-neutrality as does a single-sector model calibrated to the mean frequency and size of price changes. This amplification due to heterogeneity is driven by three features of the U.S. data: (1) the low average level of inflation in the U.S. economy, (2) the fact that the average size of price changes is large and that there is no strong correlation between the size and frequency of price change across sectors, and (3) the relatively low average frequency of price change in the U.S. economy. A single-sector menu cost model with a frequency of price change equal to the median frequency of price change in the data yields a similar degree of monetary non-neutrality to the multisector model.

The introduction of intermediate inputs raises the degree of monetary non-neutrality by another factor of three. Intermediate inputs amplify the degree of monetary non-neutrality because they generate a substantial amount of strategic complementarity in the pricing decisions of different firms. Importantly, the model can fit both the size and frequency of price change. In contrast, other popular sources of strategic complementarity—such as fixed factors of production and nonisoelastic demand curves—yield price changes that are far too small on average for reasonable parameter values. Following Ball and Romer (1990) and Kimball (1995), we divide the sources of strategic complementarity into two classes— $\omega$ -type strategic complementarity and  $\Omega$ -type strategic complementarity. We show that models with a large amount of  $\omega$ -type strategic complementarity are unable to match the average size of price changes, whereas this problem does not afflict models with a large amount of  $\Omega$ -type strategic complementarity. An empirically realistic intermediate input share can generate a substantial amount of  $\Omega$ -type strategic complementarity. In contrast, sector-specific labor markets do not generate a substantial amount of such strategic complementarity unless price adjustments are heavily staggered across sectors, something we do not observe in the data.

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