Do Nominal Rigidities Matter for the Transmission of Technology Shocks?*

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Abstract

A commonly held view is that nominal rigidities are important for the transmission of monetary policy shocks. We argue that they are also important for understanding the dynamic effects of technology shocks, especially on labor hours, wages, and prices. Based on a dynamic general equilibrium framework, our closed-form solutions reveal that a pure sticky-price model predicts correctly that hours decline following a positive technology shock, but fails to generate the observed gradual rise in the real wage and the near-constance of the nominal wage; a pure sticky-wage model does well in generating slow adjustments in the nominal wage, but it does not generate plausible dynamics of hours and the real wage. A model with both types of nominal rigidities is more successful in replicating the empirical evidence about hours, wages and prices. This finding is robust for a wide range of parameter values, including a relatively small Frisch elasticity of hours and a relatively high frequency of price reoptimization that are consistent with microeconomic evidence.

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1 Introduction

A common view holds that nominal rigidities such as sticky prices and sticky wages are important for the transmission of monetary policy shocks. We argue that nominal rigidities are also important for understanding the dynamic effects of technology shocks. In particular, we show that sticky prices and sticky nominal wages are important for generating the observed effects of technology shocks on hours, wages, and prices documented, for example, by Basu, Fernald, and Kimball (BFK, 2006).

In a provocative study, Galí (1999) reports that, in a structural vector autoregression (SVAR) model, a positive technology shock leads to a short-run decline in hours worked. He then argues that this evidence presents a challenge to the standard real business cycle (RBC) model, while being consistent with the predictions from a DSGE model with sticky prices and weak accommodation of monetary policy to the technology shock.[1] BFK (2006) provide corroborating evidence about the contractionary effects of technology shocks on hours based on an independent measure of technology. They construct a "purified" Solow residual by controlling for non-technological factors such as variable input utilization rates, non-constant returns, and imperfect competition and find that hours decline following a positive technology shock. They also argue that their evidence favors a sticky-price model.[2]

To explain the observed decline in hours, however, does not necessarily require nominal rigidities. For example, Francis and Ramey (2005) argue that the standard RBC model augmented with habit formation and investment adjustment costs is able to generate slow adjustments in aggregate output and therefore a decline in hours following a positive technology shock. Thus, based on the dynamic adjustments of hours alone, one would not be able to distinguish between the role of nominal rigidities (such as sticky prices) and the role of real rigidities (such as habit formation and investment adjustment costs) in transmitting technology shocks. We argue that, to better assess the empirical relevance of each type of frictions, it is essential to examine a broad set of labor market dynamics, including wages and prices, not just hours.

The study by BFK (2006) provides direct evidence on the adjustments of wages and prices following technology shocks. Figure 1 replicates the BFK (2006) results and reports the adjustments

[1] Christiano, Eichenbaum and Vigfusson (2004) find that, if hours enter the SVAR in levels rather than in first differences, then the response of hours to a technology shock becomes positive. Fernald (2007) offers a plausible reconciliation between these apparently conflicting results. He points out that, when the trend breaks in productivity and hours are taken into account, the response of hours to a technology shock is negative regardless of whether hours enter the SVAR in levels or in first differences.

[2] The idea that sticky prices help explain the decline in hours (or the rise in unemployment) following a positive technology shock has been recognized at least since Blanchard and Quah (1989) and Blanchard (1989): as productivity rises, sticky prices prevent output from rising as much so that hours decline.

of labor-market variables, including hours, the real wage, the nominal wage, and the price level following the BFK measure of the technology shock.[3] The figure shows that a positive technology shock leads to a modest rise in the real wage on impact, which continues rising before reaching a permanently higher level. The adjustments of the real wage are driven almost entirely by the adjustments of the price level as the nominal wage remains almost flat following the shock while the price level declines modestly on impact and continues declining for about a year until reaching a permanent lower level. The issue that we address in the current paper is then: Are nominal rigidities necessary to understand the dynamic behaviors of hours, wages, and prices following a technology shock?

To answer this question, we extend Gali's (1999) sticky-price model in two directions. First, based on the evidence that nominal wages are almost unresponsive to technology shocks, we introduce nominal wage rigidity by assuming imperfectly competitive households with respect to labor skills and nominal wage contracts à la Calvo (1983). Second, we consider a range of Frisch elasticity of hours and we show that this parameter plays a key role in determining the equilibrium responses of hours and the real wage to a technology shock. Following Galí, we assume imperfectly competitive price-setting firms and a monetary authority that adjusts the growth rate of money supply in response to changes in productivity shocks. We abstract from capital accumulation to focus on closed-form solutions. Our analytical approach allows a transparent and comprehensive reading of the mechanisms at work in generating our main findings.

We gradually build intuition about the role played by the structural ingredients of our general framework. First, we examine a model that features sticky prices only. This model is broadly similar to the one solved and analyzed by Galí (1999), except that our model features Calvo (1983) price contracts while Galí (1999) focuses on pre-determined prices. Our closed-from solution reveals that a technology improvement consistently leads to a short-run decline in hours. To the extent that money supply increases by less than one-for-one when technology improves, this result is not sensitive to variations in the elasticity of labor supply or the accommodativeness of monetary policy. Thus, Gali's (1999) finding that a sticky-price model helps generate the contractionary effects of technology shock on hours is quite robust.

Nonetheless, the sticky-price model also predicts that the response of the real wage to a technology shock can be ambiguous and the sign of the initial adjustment depends on the model's parameter values. In particular, if the Frisch elasticity of hours is low and monetary policy accommodation to the shock is weak, the positive technology shock can lead to an initial *decline* in the

[3] We are grateful to John Fernald for providing the source materials for replicating the figure.

real wage along with hours. Essentially, with sticky prices and weak monetary policy accommodation, the initial adjustments in consumption, and thus in the marginal utility of consumption are small; as hours decline and leisure rises, the marginal utility of leisure falls. Thus, the marginal rate of substitution between leisure and consumption falls on impact, and so does the real wage. The smaller the Frisch elasticity, the greater the decline in the real wage required to be consistent with the decline in equilibrium hours. With staggered price contracts, the price level declines modestly on impact, so that the initial decline in the real wage implies an even larger initial decline in the nominal wage. These patterns of adjustments in the real and nominal wages are not supported by the empirical evidence.

To generate the observed modest rise in the real wage in the sticky-price model requires a high Frisch elasticity of labor supply and a strong degree of monetary policy accommodation. However, neither seems empirically plausible. Microeconomic studies on labor supply suggest that the Frisch elasticity is small (e.g., Pencavel, 1986), so the first condition seems unlikely to be met. Regarding the second condition, we provide evidence based on an examination of the relation between the U.S. money aggregates (M1 and M2) and several alternative measures of technology shocks which shows that the degree of monetary policy accommodation is at best very weak. On this ground, we conclude that the sticky-price channel, *by itself*, cannot generate plausible dynamics of the real and nominal wages driven by technology shocks.

In light of the sluggish adjustments of the nominal wage observed empirically, we next examine the transmission mechanism of technology shocks in a sticky-wage model. With sticky wages as the only source of nominal rigidities, we find that the nominal wage remains roughly constant and the real wage rises on impact of the technology shock, representing a step in the right direction relative to the sticky-price model. Nonetheless, a pure sticky-wage model does not predict a decline in hours worked. Since prices are flexible, the technology shock leads to a one-for-one decline in the price level and, in the absence of monetary policy accommodation (i.e., constant money supply), a one-for-one increase in output with the productivity so that hours stay constant; if the monetary policy is partially accommodative to the shock, money supply will increase and output will rise even further so that hours will rise. Thus, regardless of the extent of monetary policy accommodation, the pure sticky-wage model does not predict a fall in hours.

Bringing together nominal price and nominal wage rigidities helps generate plausible dynamics for wages, prices, as well as hours following technology shocks. The inability of a pure sticky-price model to generate a weak response of the nominal wage is amended by allowing some nominal wage rigidity; the inability of a pure sticky-wage model to generate the observed decline in hours is overcome by introducing some nominal price rigidity. Even with relatively frequent price re-optimizations suggested by microeconomic studies (e.g., Bils and Klenow (2004), Klenow and Kryvtsov (2008), and Nakamura and Steinsson (2008)), the model's predicted labor market responses to technology shocks remain consistent with the empirical evidence.

The rest of the paper is organized as follows. Section 2 develops a DSGE model with sticky prices. There, we derive closed-form solutions and assesses the plausibility of the sticky-price model to match BFK's evidence on hours, wages, and prices. We also present evidence on the extent of monetary policy accommodation to technology shocks. Section 3 examines the role of sticky nominal wages in the transmission of technology shocks. We begin with a pure sticky-wage model to illustrate the mechanism and then assesses the ability of the model with both sticky prices and sticky wages in replicating the empirical evidence provided by BFK (2006). Section 4 concludes.

2 The Transmission of Technology Shocks in the Sticky-Price Model

This section presents a stylized monetary business-cycle model with sticky prices and examine the model's predicted effects of technology shocks on hours, the nominal wage, the real wage, and the price level.

2.1 The Model Economy

The economy is populated by a large number of identical, infinitely-lived households, and a large number of firms, each producing a differentiated product. The representative household is endowed with one unit of time and derives utility from consumption, real money balances, and leisure time. The consumption good is a composite of the differentiated products. Production of each type of differentiated good requires labor as the only input and is subject to a productivity shock. While the labor market is perfectly competitive, the goods market is monopolistically competitive. Firms' pricing decisions are staggered in the spirit of Calvo (1983), although our main results do not hinge upon this specific form of price rigidity.

2.1.1 The Representative Household

The representative household has preferences defined by the following utility function:

$$\mathrm{E}\sum_{t=0}^{\infty}\beta^t[\log C_t + \Phi \log \frac{M_t}{P_t} - V(N_t)], \tag{1}$$

where E is an expectations operator, $\beta \in (0,1)$ is a subjective discount factor, C_t denotes consumption, M_t/P_t denotes real money balances, and N_t denotes labor hours.

In each period t, the household faces a budget constraint

$$P_t C_t + M_t + \mathrm{E}_t D_{t,t+1} B_{t+1} \leq W_t N_t + \Pi_t + M_{t-1} + B_t - T_t, \tag{2}$$

where P_t is the price level, W_t is the nominal wage rate, Π_t is a claim to all firms' profits, and T_t is a lump-sum tax. The term B_{t+1} denotes the holdings of a one-period state-contingent nominal bond that pays one unit of currency in period $t+1$ if a particular event is realized, $D_{t,t+1}$ is the period-t price of such a bond divided by the probability of the appropriate state, so that $\mathrm{E}_t D_{t,t+1} B_{t+1}$ is the total cost of state-contingent bonds.

The consumption basket is given by

$$C_t = \left[\int_0^1 Y_t(j)^{\frac{\varepsilon_p - 1}{\varepsilon_p}} dj \right]^{\frac{\varepsilon_p}{\varepsilon_p - 1}}, \tag{3}$$

where $Y_t(j)$ denotes the output of type-j good and $\varepsilon_p > 1$ is the elasticity of substitution between differentiated products. The household's expenditure-minimization problem results in a demand schedule for a type-j good:

$$Y_t^d(j) = \left(\frac{P_t(j)}{P_t} \right)^{-\varepsilon_p} C_t, \tag{4}$$

where $P_t(j)$ denotes the price of good j, and the price level P_t is related to individual prices through $P_t = \left[\int_0^1 P_t(j)^{1-\varepsilon_p} dj \right]^{\frac{1}{1-\varepsilon_p}}$.

Solving the household's utility-maximization problem results in a labor supply equation, an intertemporal Euler equation, and a money demand equation, given respectively by

$$\frac{W_t}{P_t} = V'(N_t) C_t, \tag{5}$$

$$D_{t,\tau} = \beta^{\tau - t} \frac{C_t}{C_\tau} \frac{P_t}{P_\tau}, \tag{6}$$

and

$$\Phi \frac{1}{M_t} + \beta \mathrm{E}_t \frac{1}{P_{t+1} C_{t+1}} = \frac{1}{P_t C_t}. \tag{7}$$

2.1.2 Firms and Optimal Price-Setting

A good of type $j \in [0,1]$ is produced using labor as the input, with a production function given by

$$Y_t(j) = A_t N_t(j), \tag{8}$$

where A_t denotes a productivity shock that is common to all firms, and $N_t(j)$ is the homogeneous labor used by firm j. The shock follows a random-walk process so that

$$A_t = A_{t-1} \exp(\varepsilon_t), \tag{9}$$

where ε_t is a mean-zero, iid normal process, with a finite variance σ_a^2.

Firms are price-takers in the input markets and monopolistic competitors in the product markets. They set prices in a staggered fashion in the spirit of Calvo (1983). In particular, in period t, all firms receive an iid random signal that determines whether or not they can set a new price. The probability that firms can adjust prices is $1-\alpha_p$. By the law of large numbers, a fraction $1-\alpha_p$ of firms can set new prices in any given period.

If firm j can set a new price in period t, it chooses a price $P_t(j)$ to maximize an expected present value of its profits

$$\mathrm{E}_t \sum_{\tau=t}^{\infty} \alpha_p^{\tau-t} D_{t,\tau}[P_t(j) - V_\tau] Y_\tau^d(j), \tag{10}$$

where $V_\tau = W_\tau / A_\tau$ is the unit production cost, and $Y_\tau^d(j)$ is the demand schedule described in (4). Solving the profit maximizing problem results in an optimal pricing decision rule

$$P_t^*(j) = \mu_p \frac{\mathrm{E}_t \sum_{\tau=t}^{\infty} \alpha_p^{\tau-t} D_{t,\tau} V_\tau Y_\tau^d(j)}{\mathrm{E}_t \sum_{\tau=t}^{\infty} \alpha_p^{\tau-t} D_{t,\tau} Y_\tau^d(j)}, \tag{11}$$

where $\mu_p = \varepsilon_p / (\varepsilon_p - 1)$ measures the steady-state markup. The optimal price is thus a markup over a weighted average of the marginal costs in the current and future periods during which the price is expected to remain in effect.

Solving the cost-minimizing problem of firm j yields the demand for labor $N_t^d(j) = Y_t^d(j)/A_t$. The aggregate demand for labor is then given by

$$N_t^d = \frac{1}{A_t} \int_0^1 Y_t^d(j) dj = \frac{G_t C_t}{A_t}, \tag{12}$$

where $G_t = \int_0^1 [P_t(j)/P_t]^{-\varepsilon_p} dj$ measures price dispersion. Thus, if the rise in aggregate demand cannot catch up with productivity improvement, the aggregate demand for labor would fall.

2.1.3 Monetary Policy

Following Galí (1999), we assume that the monetary authority is allowed, but not required to adjust the growth rate of money stock in response to changes in productivity shocks. Specifically, we assume

$$\mu_t = (1-\rho)\bar{\mu} + \rho \mu_{t-1} + \gamma \varepsilon_t, \tag{13}$$

where $\mu_t = \log(M_t^s / M_{t-1}^s)$ denotes the growth rate of money supply, $\bar{\mu}$ is the mean money growth, and $\gamma \neq 0$ implies a systematic response of monetary policy to technology shocks.

2.1.4 Equilibrium

Given the monetary policy described in (13), an *equilibrium* consists of allocations C_t, N_t, B_{t+1}, and M_t for the representative household; allocations $Y_t(j)$ and $N_t(j)$, and price $P_t(j)$ for producer $j \in [0,1]$; together with prices $D_{t,t+1}$, $\bar{P}_t$, and wage W_t, that satisfy the following conditions: (i) taking the prices and the wage as given, the household's allocations solve its utility maximizing problem; (ii) taking the wage and all prices but its own as given, each producer's allocations and price solve its profit maximizing problem; and (iii) markets for bonds, money, labor, and the composite goods clear.

We focus on a symmetric equilibrium in which all firms who can adjust prices in a given period make identical pricing decisions. Thus, we do not have to keep track of the firm-specific index j and we can write the pricing decisions as P_t^* in place of $P_t^*(j)$.

2.2 The Sticky-Price Channel

We now examine the sticky-price channel for the transmission of technology shocks. We examine, both analytically and numerically the responses of hours, the real wage, and the nominal wage following a technology shock.

2.2.1 Theoretical Properties of the Sticky-Price Model

We first examine the theoretical properties of the sticky-price model for the adjustment of hours, the nominal wage, the real wage, and the price level following a technology shock and we assess the plausibility of these theoretical implications in light of the empirical evidence provided by BFK (2006). In the next subsection, we evaluate the model's performance along these dimensions under empirically plausible values of the parameters. For our purpose, we consider small shocks so that the equilibrium conditions can be approximated by log-linearizing around a zero-inflation steady state.[4] Further, for analytical convenience, we set $\rho = 0$ in the money growth rule (13), so that deviations of the money growth rate from its steady state level is proportional to productivity growth. Or equivalently, given that the productivity shock follows a random walk process, so does the money stock under the assumption that $\rho = 0$. This allows us to characterize the equilibrium dynamics using a closed-form solution. We relax this assumption when we assess the quantitative implications of the sticky-price model in the next subsection.

[4] Allowing for positive steady-state inflation does not change the qualitative results (not reported).

We begin with the Phillips-curve relation obtained from log-linearizing the optimal pricing decision rule (11)

$$\pi_t = \beta \mathrm{E}_t \pi_{t+1} + \kappa_p (c_t - \bar{c}_t), \tag{14}$$

where lower-case variables denote the log-deviations of the upper-case variables from steady state, $\pi_t = p_t - p_{t-1}$ denotes the inflation rate, $\bar{c}_t = a_t$ is the natural rate of output. The parameter $\kappa_p = \lambda_p(1+\eta)$ determines the response of real marginal cost to changes in output, where $\eta = V''(N)N/V'(N)$ is the inverse labor-supply elasticity and $\lambda_p = (1-\beta\alpha_p)(1-\alpha_p)/\alpha_p$ is the elasticity of pricing decisions with respect to real marginal cost. Note that κ_p increases with η, the inverse labor supply elasticity. A smaller labor supply elasticity implies a larger value of η and thus a larger κ_p, so that the marginal cost is more responsive to changes in aggregate demand, and there is less endogenous nominal price rigidity.

Next, we log-linearize the intertemporal money demand decision (7) to obtain

$$p_t + c_t = (1-\beta) m_t + \beta \mathrm{E}_t (p_{t+1} + c_{t+1}). \tag{15}$$

Under our assumption that $\rho = 0$ in the monetary policy rule (13), the money supply follows a random-walk process, as does the technology shock. Then, (15) reduces to

$$p_t + c_t = (1-\beta) \sum_{j=0}^{\infty} \beta^j \mathrm{E}_t m_{t+j} = m_t. \tag{16}$$

Note that, this apparently static aggregate demand relation is not an *ad hoc* assumption, but rather an *equilibrium* outcome. It is obtained under the assumptions of separable period-utility function, log-utilities in consumption and real money balances, and the random-walk property of money stocks inherited from the technology shock process.

The system of equilibrium conditions (14) and (16), along with the monetary policy rule $m_t = \gamma a_t$ can be combined to obtain a solution for the dynamics of the price level. This is given by

$$p_t = \theta_p p_{t-1} + (1-\theta_p)(\gamma - 1) a_t. \tag{17}$$

where θ_p is the stable root of the quadratic polynomial $\beta\theta^2 - (1+\beta+\kappa_p)\theta + 1 = 0$. Thus, the price level falls on impact of a positive technology shock if and only if $\gamma < 1$. A larger θ_p implies greater strategic complementarity in firms' pricing and thus more persistence in the price (and inflation) dynamics and a smaller response of the price level (and of inflation) to technology shocks.

Given the solution for p_t, we obtain the solution for c_t by using (16). It then follows from $n_t = c_t - a_t$ that the solution for employment is given by

$$n_t = \theta_p n_{t-1} + (\gamma - 1)\theta_p \varepsilon_t. \tag{18}$$

Therefore, as stated by Galí (1999), a technology improvement can lead to a fall in employment if and only if $\gamma < 1$. Further, for a larger value of θ_p, employment becomes more persistent and, for any given $\gamma \neq 1$, more responsive to the technology shock.

As a point of departure from Galí (1999), we also examine the dynamic response of real and nominal wages to technology shocks. Using the method of undetermined coefficients, we obtain the initial response of the real wage (denoted by ω_t):

$$\omega_0 = 1 - \theta_p(1+\eta)(1-\gamma). \tag{19}$$

The impact effect of a technology shock on the real wage is thus ambiguous, depending on the parameter values. The real wage falls on impact if monetary policy accommodation to the technology shock is weak (i.e., γ is small), the Frisch elasticity of hours is small (i.e., η is large), or the strategic complementarity is strong (i.e., θ_p is large).

Thus, in response to a positive technology shock, the stickiness in price-setting implies sluggishness in output adjustment as long as γ is small. For a small value of γ, output adjustment cannot catch up with the technology improvement, leading to a lower demand for labor at any given real wage. The lower demand for labor puts a downward pressure on the equilibrium real wage. Since c_t rises, there is also an income effect on labor supply that tends to offset the fall in the real wage, rendering the net effect ambiguous. Specifically, the net effect on the real wage depends on the strength of the income effect (that depends negatively on the endogenous price stickiness measured by θ_p and positively on the degree of monetary policy accommodation measured by γ) relative to that of the substitution effect (that depends positively on the curvature coefficient of the labor supply curve η).

For plausible parameter values, as we show below, the real wage indeed falls along with employment in the sticky-price model. As the price level falls (for $\gamma < 1$), the decline in the real wage after the shock implies an even stronger decline in the nominal wage, making it difficult for the sticky-price model, by itself, to explain the modest rise in the real wage on impact of the technology shock and the weak adjustment in the nominal wage.

2.2.2 Calibration

We now assess the quantitative predictions of the sticky-price model under empirically plausible parameter values. We first consider a set of baseline calibrated parameters, and then examine the robustness of the results.

The parameters to be calibrated include β, the subjective discount factor; α_p, the Calvo probability of price non-reoptimization; ε_p, the elasticity of substitution between differentiated products;

η, the inverse elasticity of labor supply; and the monetary policy parameters ρ and γ. The calibrated values are summarized in Table 1.

Since we have a quarterly model in mind, we set $\beta = 0.99$ so that the steady state annual real interest rate is 4 percent. We set $\alpha_p = 0.75$ so that the average duration of the price contracts is 4 quarters. The parameter ε_p determines the steady-state markup of prices over marginal cost, with the markup given by $\mu_p = \varepsilon_p/(\varepsilon_p - 1)$. Recent studies by Basu and Fernald (2002) suggest that the value-added markup, controlling for factor capacity utilization rates, is about 1.05; whereas without any utilization correction, the value-added markup is about 1.12. Some other studies suggest a higher value-added markup of about 1.2 (without corrections for factor utilization) (e.g., Rotemberg and Woodford, 1997). Since we do not focus on variations in factor utilization, in light of these studies, we set $\varepsilon_p = 10$ so that $\mu_p = 1.1$. The parameter η corresponds to the inverse labor supply elasticity. Most empirical studies suggest that this elasticity is small and lies well below one, so that η is above one. We set $\eta = 2$ as a benchmark value and also consider a range of η between 1 and 5, corresponding to a labor supply elasticity in the range between 0.2 and 1, consistent with evidence on the elasticity of labor supply obtained from micro data (e.g., Pencavel, 1986).[5] For the purpose of illustration, we set $\rho = 0.6$ and $\gamma = 0$ as a benchmark. In our sensitivity analysis, we allow γ to vary in the broad range between 0 and 1.

Figure 4 plots the impulse responses of hours, the nominal wage, the real wage, and the price level following a positive technology shock under the calibrated parameters. Evidently, both the nominal wage and the real wage fall along with employment, and the fall in the nominal wage is greater than that of the real wage. The fall in hours is supported by empirical evidence, but the declines in wages, both nominal and real, are not.

Figure 4 plots the impact effects of the shock on hours, the real wage, and the nominal wage as the policy parameter γ varies from 0 to 1 and the inverse labor supply elasticity η varies from 1 to 5. The figure reveals that the sticky-price model consistently predicts the fall in hours under all configurations of these parameters. The impact effects on the real wage and the nominal wage are more ambiguous. Consistent with our analytical solutions for the wage dynamics, the impact effect tends to be more negative if γ is small or η is large. Given the smallest value of η we consider plausible (i.e., $\eta = 1$), the sticky-price model is able to generate a rise in the real wage if γ is large enough (above 0.3). But with large values of γ, the nominal wage also rises along with the real wage, which is at odds with the evidence that the former does not adjust much while the latter rises significantly following technology shocks.

[5] The results are robust even when we extend the lower bound of η to 0.5 (not reported).

2.2.3 The Extent of Monetary Accommodation

Since the predictions of the sticky-price model depends on how accommodative monetary policy is, it is important get a sense of how large γ is. That is, how accommodative was U.S. monetary policy to technology shocks? One way to answer this question is to examine the relation between the growth rate of a measure of U.S. money aggregates and an appropriate measure of technology shocks. Without loss of generality, we use M2 as a measure of U.S. money aggregate, with a sample period from 1959 to 2003 (at monthly frequency). This series is obtained from the FRED II database published by the St. Louis Federal Reserve Bank. We use two alternative measures of technology shocks. The first measure is constructed by Galí and Rabanal (2004) with a sample period from 1950 to 2002 (at quarterly frequency), and the second is the "purified" technology measure constructed by BFK (2006), which has a sample period from 1949 to 1996 (at annual frequency).[6]

Figure 4 presents scatter plots of M2 growth rate and the two alternative measures of technology shocks, with appropriate data frequencies and sample periods. The plots suggest a weak correlation between the money growth rate and the technology measures. In other words, γ is likely to be small.

To obtain a formal estimate of γ, we run an OLS regression of the M2 growth rates on the technology shock series. In particular, we estimate the monetary policy rule specified in (13), which, for ease of reference, is rewritten here:

$$\mu_t = (1-\rho)\bar{\mu} + \rho\mu_{t-1} + \gamma\varepsilon_t. \tag{20}$$

Using Galí-Rabanal's technology measure, the point estimates are $\hat{\rho} = 0.61(0.06)$ and $\hat{\gamma} = 0.10(0.05)$, where the numbers in parentheses are standard errors. Using the BFK measure produces point estimates of $\hat{\rho} = 0.60(0.14)$ and $\hat{\gamma} = 0.13(0.33)$. The 95 percent confidence interval for $\hat{\gamma}$ is 0 to 0.2 with Galí-Rabanal's measure, and -0.53 to 0.79 with the BFK measure. It appears that the estimates for γ are small and may even be statistically insignificant, which provides the basis for our baseline calibration of $\gamma = 0$.[7]

Going back to Figure 4, we see that even if we use the higher point estimate of $\gamma = 0.13$, the responses of the nominal wage and the real wage are still negative for all values of η. The fall in the nominal wage is greater than that of the real wage, and is much sharper than is the fall in the price level. Although it can be argued that there is some empirical support for the decline in hours, the patterns of adjustments in the nominal wage and the real wage obtained from the pure sticky-price model are simply not supported by the evidence.

[6]We are grateful to Susanto Basu and Jordi Galí for kindly providing us with the data.

[7]We have also used M1 data in the regression and obtained very similar results (not reported).

3 Adding Nominal Wage Rigidity

The sluggish responses of the nominal wage to the technology shock suggests that nominal wage rigidity can be important. We now introduce sticky nominal wages in the model and examine the sticky-wage channel in the transmission of technology shocks.

We assume that the labor market, like the goods market, is monopolistically competitive. There is a continuum of households, each endowed with a differentiated labor skill indexed by $i \in [0, 1]$, with a utility function similar to (1) (with all variables in the utility function indexed by i). Production of goods requires a composite labor as the input, and is subject to a productivity shock. The production function is the same as in (8), with the composite labor given by

$$N_t = \left(\int_0^1 N_t(i)^{\frac{\varepsilon_w - 1}{\varepsilon_w}} di \right)^{\frac{\varepsilon_w}{\varepsilon_w - 1}}, \tag{21}$$

where $\varepsilon_w > 1$ is the elasticity of substitution between differentiated skills. Solving firms' cost-minimizing problem results in a demand schedule for labor skill of type i. It is given by

$$N_t^d(i) = \left(\frac{W_t(i)}{W_t} \right)^{-\varepsilon_w} N_t, \tag{22}$$

where $W_t(i)$ is the nominal wage for a type i labor skill, and W_t is the wage index that is related to individual wages by $W_t = \left(\int_0^1 W_t(i)^{1-\varepsilon_w} di \right)^{\frac{1}{1-\varepsilon_w}}$.

In each period, each household receives an iid random signal that enables it to adjust its nominal wage with probability $1 - \alpha_w$, taking the demand schedule for labor skill (22) as given. It follows from the law of large numbers that, in each period, a fraction $1 - \alpha_w$ of all households can set new wages. The optimal wage decision rule is given by

$$W_t^*(i) = \mu_w \frac{\mathrm{E}_t \sum_{\tau=t}^{\infty} \alpha_w^{\tau-t} D_{t,\tau} MRS_\tau(i) N_\tau^d(i)}{\mathrm{E}_t \sum_{\tau=t}^{\infty} \alpha_w^{\tau-t} D_{t,\tau} N_\tau^d(i)}, \tag{23}$$

where $\mu_w = \varepsilon_w / (\varepsilon_w - 1)$ measures the steady-state wage markup, and $MRS = V'(N)C$ denotes the marginal rate of substitution between leisure and consumption. The optimal wage is thus a constant markup over a weighted average of the MRS's in the current and future periods during which the wage is expected to remain in effect.

We focus on log-linearized equilibrium conditions around a zero-inflation steady state. In the model with both sticky prices and sticky wages, the equilibrium conditions are summarized below:

$$\pi_t = \beta \mathrm{E}_t \pi_{t+1} + \lambda_p \tilde{\omega}_t, \tag{24}$$

$$\pi_{wt} = \beta \mathrm{E}_t \pi_{w,t+1} + \frac{\lambda_w}{1 + \eta \varepsilon_w} [(1 + \eta) \tilde{c}_t - \tilde{\omega}_t], \tag{25}$$

$$\tilde{\omega}_t = \tilde{\omega}_{t-1} + \pi_{wt} - \pi_t - \Delta a_t, \tag{26}$$

$$(1-\beta)(\tilde{c}_t - \tilde{m}_t) = \beta \mathrm{E}_t(\pi_{t+1} + \Delta\tilde{c}_{t+1}), \tag{27}$$

$$\Delta\tilde{m}_t = \mu_t - \pi_t - \Delta a_t, \tag{28}$$

along with the monetary policy rule (13). In these expressions, $\pi_{wt} = w_t - w_{t-1}$ denotes the wage inflation rate, $\tilde{\omega}_t$ denotes the real-wage gap, $\tilde{c}_t$ denotes the output gap, $\tilde{m}_t$ denotes the real-balance gap, and $\lambda_w = (1-\beta\alpha_w)(1-\alpha_w)/\alpha_w$ is a parameter that determines the responsiveness of wage-setting decisions to the marginal rate of substitution between leisure and consumption. Equations (24) and (25) are derived from optimal price- and wage-setting decisions and are sometimes known as the price-Phillips curve and the wage-Phillips curve, respectively. Equation (26) describes the law of motion of the real-wage gap. Equation (27) is derived from the money demand relation. Finally, (28) describes the law of motion of the real-balance gap.

3.1 The Sticky-Wage Channel

To examine the potential ability of the model with nominal wage rigidity in explaining BFK's evidence, we consider various degrees of price rigidity. We begin with the extreme case where prices are perfectly flexible (i.e., $\alpha_p = 0$). In this case, the pricing decision is given by $p_t = w_t - a_t$, so that the real wage rises one-for-one with the technology shock, and the real-wage gap is closed. To help obtain the equilibrium dynamics of hours, the price level, and the nominal wage, we assume that the monetary authority follows the money growth rule (13) and that $\rho = 0$.

First, since the real-wage gap is closed under flexible prices, we can rewrite the wage-Phillips curve relation (25) as

$$\pi_{wt} = \beta \mathrm{E}_t \pi_{w,t+1} + \kappa_w(c_t - a_t). \tag{29}$$

where $\kappa_w = \lambda_w(1+\eta)/(1+\eta\varepsilon_w)$. Using the pricing decision equation $p_t = w_t - a_t$, this equation can be rewritten in terms of price inflation:

$$\pi_t + \Delta a_t = \beta \mathrm{E}_t(\pi_{t+1} + \Delta a_{t+1}) + \kappa_w(c_t - a_t).$$

Solving for the price level, we obtain

$$p_t = \theta_w p_{t-1} + (1-\theta_w)(\gamma - 1)a_t - \theta_w \Delta a_t, \tag{30}$$

where $\theta_w \in (0,1)$ is the stable root of the quadratic polynomial $\beta\theta^2 - (1+\beta+\kappa_w)\theta + 1 = 0$. Given the solution for p_t, we use the aggregate demand relation (16) to obtain c_t, and the production function to obtain n_t. The solution for hours is given by

$$n_t = \theta_w n_{t-1} + \theta_w \gamma \varepsilon_t. \tag{31}$$

Thus, with perfectly flexible prices and sticky nominal wages, the hours response to technology shocks is non-negative as long as $\gamma \geq 0$.

Since the real wage rises one-for-one with productivity and the impact effect on the price level implied by (30) is $(1-\theta_w)\gamma - 1$, the impact effect on the nominal wage is given by $(1-\theta_w)\gamma$. Since $\theta_w < 1$, the response of the nominal wage, as is that of hours, is non-negative provided that $\gamma \geq 0$. Further, since our evidence suggests that γ is small, the response of the nominal wage to the technology shock is also small. This prediction from the sticky-wage model seems to be supported by the BFK (2006) evidence.

Yet, the sticky-wage model's predicted adjustment in the real wage does not align well with the empirical evidence. In the data, the real wage rises modestly on impact, and continues rising thereafter until reaching the new steady state. In the model, the real wage rises instantaneously to the new steady state on impact of the shock. This problem occurs mainly because price adjustments are assumed to be perfectly flexible. Moreover, the sticky-wage model fails to generate a fall in hours when technology improves.

3.2 The Joint Implications of Sticky Wages and Sticky Prices

We now consider the more general case with some price rigidity along with the nominal wage rigidity. In this case, the equilibrium dynamics are the solution to the system of equilibrium conditions (24)-(28), along with the monetary policy rule (13). To solve the model, we use the calibrated parameter described in the previous section, and calibrate two additional parameters that are unique to nominal wage rigidity: we set $\alpha_w = 0.75$ so that the average duration of nominal wage contract is four quarters, as suggested by empirical evidence (e.g., Taylor (1999)); and we set $\varepsilon_w = 4$, so that a 1 percent rise in relative nominal wages would result in a 4 percent fall in relative hours worked, in light of the microeconomic evidence presented by Griffin (1992, 1996) (see also Huang and Liu (2002)). Again, we consider $\eta = 2$ and $\gamma = 0$ as a baseline calibration and examine the sensitivity of the results as η varies in the range between 1 and 5 and γ in the range between 0 and 1. Finally, in light of the microeconomic evidence that prices are adjusted fairly frequently, we consider a shorter price-contract duration of 2 quarters as well as the standard calibration of 4 quarters.

Figure 4 plots the impulse responses of hours, wages, and prices following a positive technology shock, with various degrees of price rigidity. In the extreme case with flexible prices, as we have shown analytically, hours does not change. When the average duration of price contracts is 2 quarters, hours falls. Increasing price rigidity to 4 quarters of contracts magnifies the fall in hours. The response of the real wage stays positive as we vary the degrees of price rigidity, although the initial response is more dampened as the length of price contracts increases. Introducing price rigidity makes the response of the nominal wage become negative, although the magnitude of the nominal wage response remains quite small relative to the changes in hours and the real wage, as observed in BFK.

In this sense, the model with nominal wage rigidity, along with some price rigidity, is more successful than the pure sticky-price model in explaining the evidence reported in BFK, and the required price rigidity is rather modest.

Now, how robust are these results if we consider a broader range of key parameter values? Figure 4 plots the impact effect on hours, the real wage, and the nominal wage as η varies from 1 to 5 and γ varies from 0 to 1. For most of the parameter values, the model consistently predicts that hours falls, the real wage rises, and the nominal wage does not change much following technology shocks, just as the evidence says.

4 Conclusion

We have examined the role of nominal rigidities in the forms of sticky prices and sticky nominal wages in explaining the dynamic effects of technology shocks on hours as well as wages and prices. We find that these nominal rigidities, which are commonly believed to be important for the transmission of monetary policy shocks in the literature, are also important for the transmission of technology shocks. Our finding illustrates the importance of nominal rigidities in shaping the business cycle. It calls for a better understanding of the sources of these nominal rigidities in order to understand the sources of the business cycle fluctuations.

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Table 1.

Calibrated parameter values

Preferences:	$\eta = 2$,	$\beta = 0.99$
Nominal contract duration:	$\alpha_p = 0.75$,	$\alpha_w = 0.75$
Elasticities of substitution:	$\epsilon_p = 10$,	$\epsilon_w = 4$
Money growth rule:	$\rho = 0.60$,	$\gamma = 0$

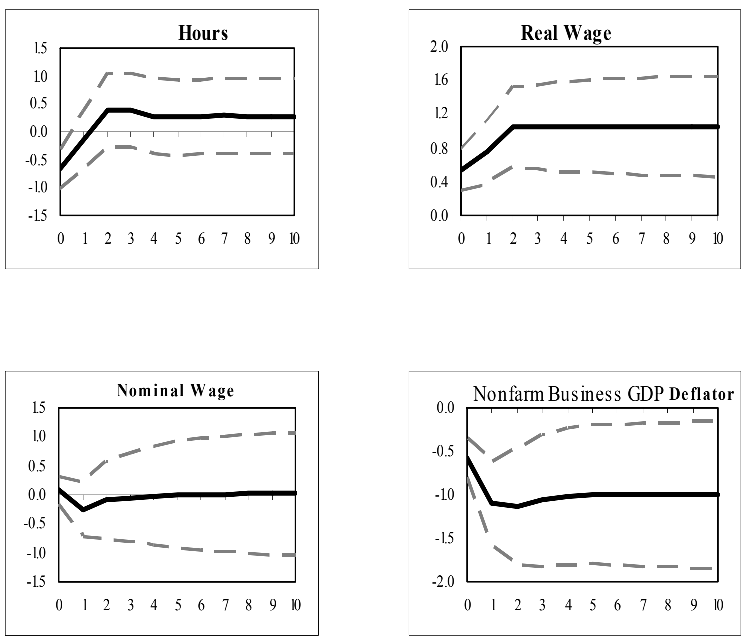

Figure 1:—Impulse responses to the BFK technology shock. Data are annual time series from 1949 to 1996, taken from Basu, Fernald, and Kimball (2006).

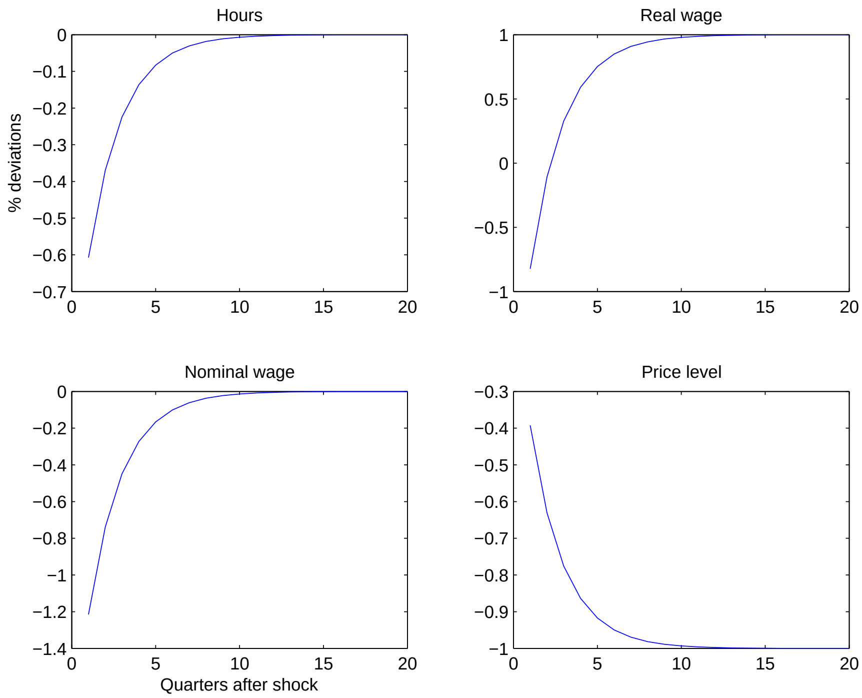

Figure 2:—Impulse responses of labor market variables to a positive technology shock in the sticky-price model.

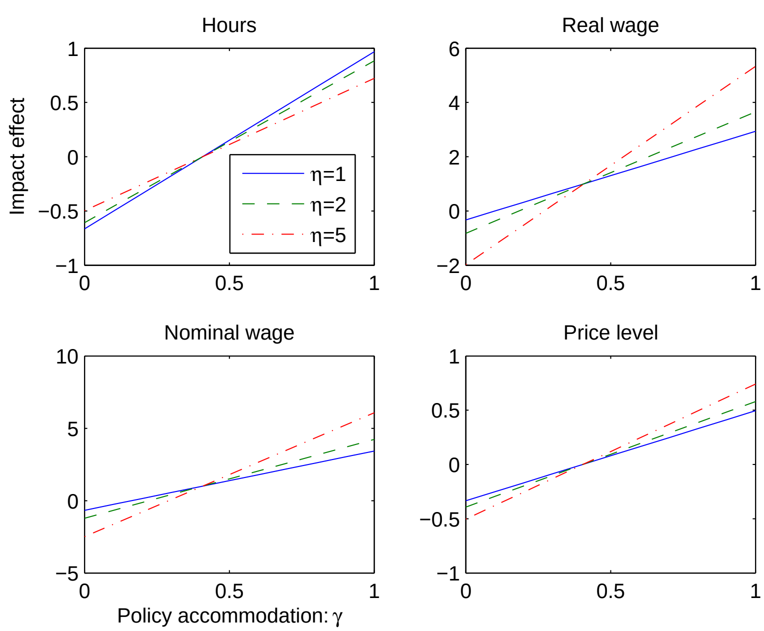

Figure 3:—Impact effects of a positive technology shock on labor market variables in the sticky-price model for various values of η (the Frisch elasticity of labor hours) and γ (the monetary-policy accommodation parameter).

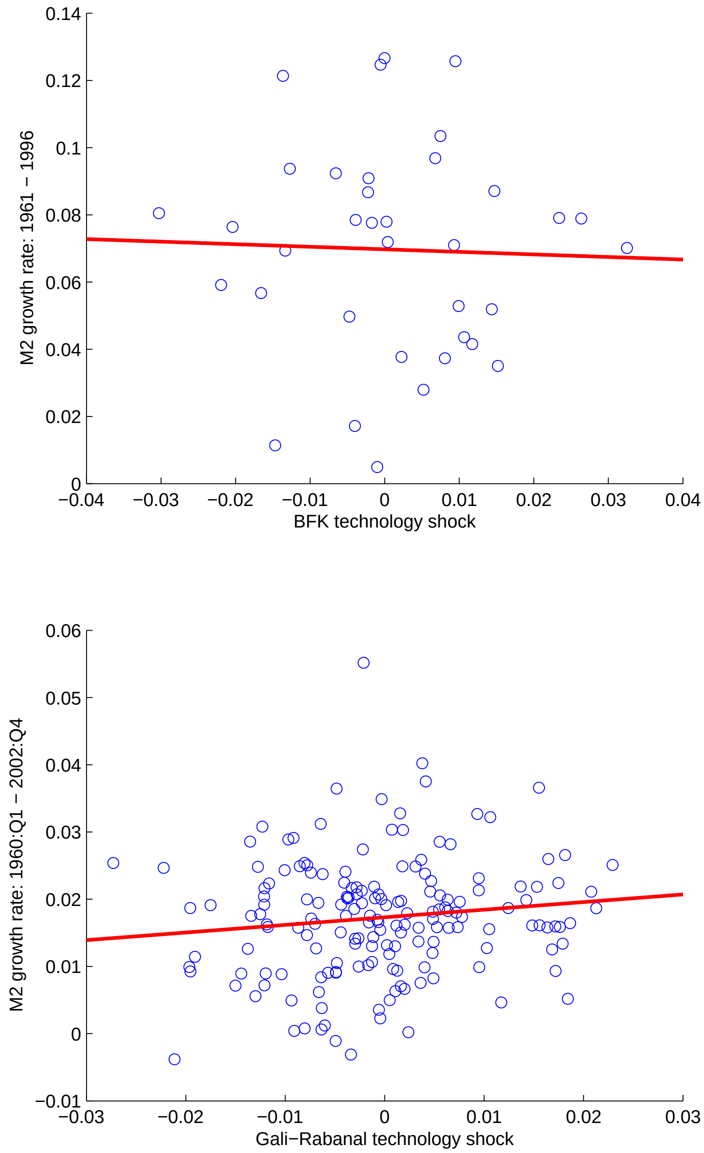

Figure 4:—Money growth rate and technology shocks. The upper panel is a scatter plot of the M2 growth and the BFK (2006) technology shock (annual frequency, 1960-1996). The lower panel is a scatter plot of the M2 growth and the Gali-Rabanal (2004) technology shock (quarterly frequency, 1960:Q1 - 2002:Q4). The solid lines are the linear fits.

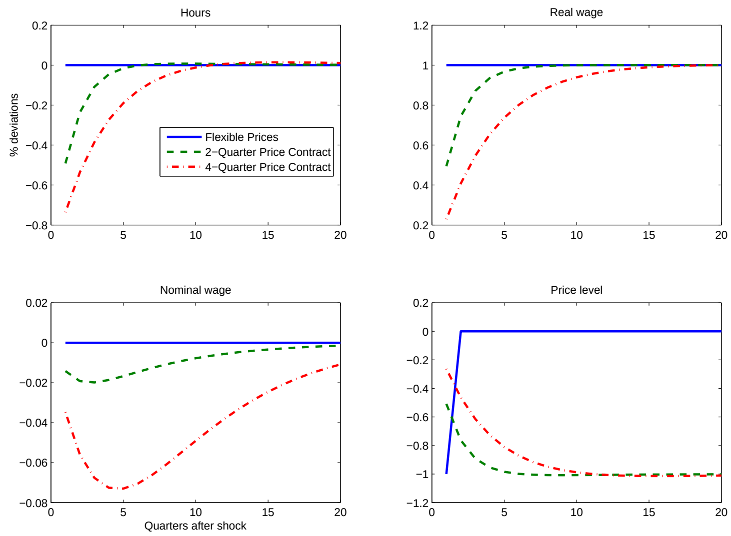

Figure 5:—Impulse responses of labor market variables to a positive technology shock in the benchmark model with sticky prices and nominal wages.

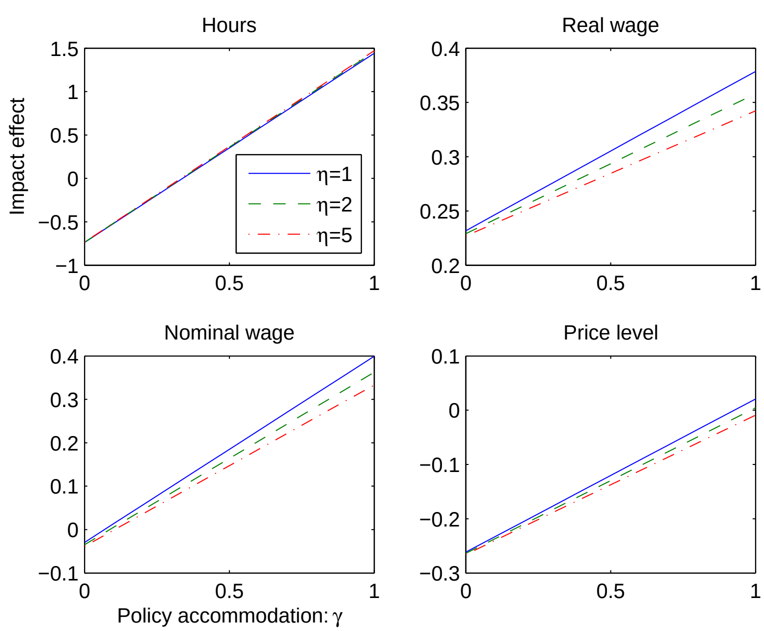

Figure 6:—Impact effects of a positive technology shock on labor market variables in the benchmark model with sticky prices and nominal wages for various values of η (the Frisch elasticity of labor hours) and γ (the monetary-policy accommodation parameter).