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Strategic Interaction among Heterogeneous Price-Setters in an Estimated DSGE Model*

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Abstract

We consider a dynamic stochastic general equilibrium (DSGE) model in which firms follow one of four price-setting regimes: sticky prices, sticky-information, rule-of-thumb, or full-information flexible prices. The parameters of the model, including the fractions of each type of firm, are estimated by matching the moments of the observed variables of the model to those found in the data. We find that sticky-price firms and sticky-information firms jointly account for over 80% of firms in the model. We compare the performance of our hybrid model to pure sticky-price and sticky-information models along various dimensions, including monetary policy implications.

JEL Codes: E3, E5
Keywords: Heterogeneity, Price-setting, DSGE.

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1 Introduction

The nature of price-setting decisions made by firms has long played a pivotal role underlying controversies in macroeconomics. Whereas real business cycle models assume that firms with full information are free to set prices optimally at all times, New Keynesian models are typically defined by departures from the assumption of flexible prices. Recent work has also emphasized the implications of deviating from the assumption of full-information in price setting.[1] This paper is motivated by the idea that a single assumption about firms' price-setting decision processes may be insufficient to adequately capture macroeconomic dynamics by missing potentially important interactions among heterogeneous firms. Indeed, firm-level evidence indicates striking heterogeneity in price setting as well as significant information costs.[2] We develop and estimate a dynamic stochastic general equilibrium model that allows for four commonly assumed price-setting sectors to coexist and interact via their price-setting decisions. Our results indicate that 1) the hybrid model fits the data substantially better than any of the models consisting solely of one type of firm; 2) sticky-price and sticky-information firms account for more than 80% of all firms in the hybrid model; 3) neither rule-of-thumb nor flexible-price full-information firms are important to match the moments of the data; 4) strategic interaction between different price setting practices is qualitatively and quantitatively important.

To assess the relative importance of heterogeneity in the price-setting behavior of firms, we consider a continuum of monopolistic producers of intermediate goods, divided into four segments, each of which uses a different price-setting approach. These include sticky-prices, sticky-information, rule-of-thumb, and full-information flexible-price firms.[3] This setup is nested in an otherwise standard New Keynesian model with a representative consumer and a central bank. The parameters of the model, including the share of each type of firm, are estimated jointly using a method of moments approach. This delivers a set of predicted moments for the observable variables that can be directly compared to those of the data.

Because we allow for these four types of firms to coexist, our model nests many price-setting models considered in the literature. For example, sticky-price models are frequently augmented with rule-of-thumb firms to better match the inflation inertia observed in the data, but the relative importance of forward-looking versus backward-looking behavior has been much debated.[4] Our result that sticky-price firms account for approximately sixty percent of firms is consistent with the findings of much of this literature, but we argue that sticky price firms should be modeled along with sticky information firms rather than rule-of-thumb firms to generate inflation inertia.

Flexible-price full-information firms are included to capture the potential importance of heterogeneity in rates at which prices and information are updated. Bouakez et al (2006), Carvalho (2006) and Aoki (2001) demonstrate that heterogeneity in price stickiness across sectors affects the dynamics and optimal monetary policy of a sticky price model respectively. By including flexible price firms, our model nests a simple case of such heterogeneity. The fact that these types of firms receive an estimated share of only 8% indicates that heterogeneity of this sort is relatively unimportant to match the moments of the data.

The presence of sticky-price, sticky-information, and rule-of-thumb firms also nests empirical work to assess the factual support for the New Keynesian Phillips Curve (NKPC) versus the Sticky Information Phillips Curve (SIPC). While results have been either ambiguous or favored the NKPC (Korenok (2008), Kiley (2007b) and Coibion (2010)), most of this literature has assumed that either the NKPC or SIPC (or their weighted average) form the true models without allowing for coexistence of different price setting mechanisms. We build on this approach by allowing for both sticky-price and sticky-information firms to coexist and interact via strategic complementarities in price-setting.

Our finding that both types of firms are required to best match the data thus calls into question much of this previous work focused only on one model or the other.

By considering a hybrid model with sticky-prices and sticky-information, this paper is most closely related to recent work by Dupor et al (forthcoming), Knotek (2009), and Klenow and Willis (2007), each of which superimpose delayed information updating as in Mankiw and Reis (2002) upon firms already facing nominal rigidities: menu costs in Knotek (2009) and Klenow and Willis (2007) and time-dependent updating in Dupor et al (forthcoming). Each finds empirical evidence for sticky-prices and sticky-information. Thus, our results complement their findings. However, our approach differs from theirs in three important aspects. First, whereas each of these papers considers models in which all firms are subject to both sticky prices and sticky information, our model allows for sticky-price and sticky-information firms to coexist and interact via strategic complementarities in price-setting, but does not allow for any firm to have both sticky-prices and sticky-information. While we view our approach as a better approximation to the fact that the relative importance of pricing and informational rigidities varies across firms, and thus are likely to be best modeled via different pricing assumptions, whether sticky-prices and sticky-information are best integrated vertically (as in Klenow and Willis (2007), Knotek (2009) and Dupor et al (forthcoming)) or horizontally is an as-of-yet unexplored empirical question. Second, our model is more general since it nests sticky-price, sticky-information, and rule-of-thumb firms as well as flexible-price full-information firms, whereas Klenow and Willis (2007), Knotek (2009) and Dupor et al (forthcoming) exclude either rule-of-thumb or flexible-price full-information or both types of firms. Third, neither Knotek (2009) nor Dupor et al (forthcoming) use fully-specified DSGE models for their empirical results and thus are not able to explore the implications of heterogeneous price-setting for the sources of business cycles and optimal monetary policy.

To estimate our DSGE model, we make use of the dynamic auto- and cross-covariances of observable variables. These moments provide important insights about the lead-lag structure of economic relationships. By comparing the ability of the estimated hybrid model and estimated pure models to match these moments of the data, one contribution of the paper is being able to assess *why* the data prefer our hybrid model over pure sticky-price or sticky-information models. For example, the moments of the data indicate that inflation leads output growth and interest rates. This stylized fact is the primary reason why sticky-price firms account for such a large fraction of firms since sticky-prices induce more-forward looking behavior than alternative price-setting setups.

We also consider the implications of our results for optimal monetary policy. While much work has been devoted to studying optimal monetary policy for sticky-price models, and some work has extended this type of analysis to sticky-information, Kitamura (2008) is the only other paper which considers optimal monetary policy in a hybrid sticky-price and sticky-information model and does so using the vertically integrated hybrid model of Dupor et al (forthcoming).[5] Based on our estimated DSGE model, we find that there could be gains in welfare if the central bank used policy rules different from the estimated Taylor rule. In particular, our simulations indicate improvements when the central banker has a more aggressive response to inflation or incorporates an element of price level targeting in his or her reaction function. We show that using pure sticky-price or sticky-information models can mislead the central banker about potential gains from using alternative policy rules in the presence of heterogeneous price setting. The fact that Kitamura (2008) reaches a similar conclusion using an alternative integration of price and informational rigidities supports the notion that accounting for both types of rigidities has important monetary policy implications which are not adequately addressed in either pure sticky-price or pure sticky-information models. Finally, we find that there is little penalty from using a policy with a response to inflation that is uniform across sectors relative to policy rules with differential responses.

The structure of the paper is as follows. In section 2, we present the model. Section 3 discusses the empirical methodology. Our benchmark estimates, discussion, and robustness analysis are in section 4. Section 5 considers the implications of our results for optimal monetary policy while section 6 concludes.

2 Model

The model has three principal types of agents: consumers, firms, and the central bank. The consumer's problem is modeled as a representative agent with internal habit formation. Production is broken into final goods and intermediate goods. Production of the final goods is perfectly competitive whereas the intermediate goods are produced by a continuum of monopolistic producers. The latter follow different price-setting rules. Finally, the central bank sets interest rates according to a Taylor (1993) rule.

2.1 Consumer's Problem

The representative agent seeks to maximize the present discounted value of current and future utility levels

$$\max_{\{C_{t+k}, N_{t+k}(i), H_{t+k}\}_{k=0}^{\infty}} E_t \sum_{k=0}^{\infty} \beta^k \left[e^{g_{t+k}} \ln(C_{t+k} - hC_{t+k-1}) - \frac{1}{1+1/\eta} \int_0^1 N_{t+k}^{1+1/\eta}(i) di \right],$$

where C_t is consumption at time t, $N_t(i)$ is labor supplied to intermediate goods firm i, h is the degree of internal habit formation, η is the Frisch labor supply elasticity, β is the discount factor, and g_t is a shock to the marginal utility of consumption. We allow for labor to be supplied individually to specific firms to generate strategic complementarity in price setting. Consumption enters in a logarithmic form to be consistent with a balanced growth path. Each period, the consumer faces the following budget constraint

$$C_{t+k} + \frac{H_{t+k}}{P_{t+k}} \leq \int_0^1 N_{t+k}(i) \frac{W_{t+k}(i)}{P_{t+k}} di + \frac{H_{t+k-1}}{P_{t+k}} R_{t+k-1} + T_{t+k},$$

where H_t is the stock of risk-free bonds held at time t, R_t is the gross nominal interest rate earned on bonds in the subsequent period, $W_t(i)$ is the nominal wage earned from labor supplied to intermediate goods firm i, and T_t consists of profits returned to the consumer. Finally, P_t is the price of the consumption good at time t.

Defining Λ_t to be the shadow value of wealth, the first-order conditions with respect to each control variable are

Consumption $$\Lambda_t = \frac{e^{g_t}}{C_t - hC_{t-1}} - \beta h E_t \frac{e^{g_{t+1}}}{C_{t+1} - hC_t}, \tag{1}$$

Labor Supply $$N_t^{1/\eta}(i) = \Lambda_t (W_t(i)/P_t), \tag{2}$$

Bonds $$\Lambda_t = \beta E_t \left[\Lambda_{t+1} R_t (P_t / P_{t+1}) \right]. \tag{3}$$

2.2 Production

The final good is produced by a perfectly competitive industry using a continuum of intermediate goods through a Dixit-Stiglitz aggregator $Y_t = (\int_0^1 Y_t(j)^{(\theta-1)/\theta} dj)^{\theta/(\theta-1)}$. This yields the following price level $P_t = (\int_0^1 P_j(j)^{1-\theta} dj)^{1/(1-\theta)}$. The demand facing an intermediate producer j is then given by $Y_t(j) = \left(P_t(j)/P_t\right)^{-\theta} Y_t$.

We assume that intermediate goods producers have a production function that is linear in labor $Y_t(j) = A_t N_t(j)$. Despite the presence of firm-specific labor supply, we assume that firms treat wages as exogenously determined. The optimal frictionless price ($P_t^{\#}$) is a markup $\mu \equiv \theta/(\theta-1)$ over firm-specific nominal marginal costs, where the latter are given by $MC_t(j) = W_t(j)/A_t$. Eliminating the firm-specific elements of marginal cost by substituting in the labor supply condition and the firm-level demand yields the following relationship between real firm-specific marginal costs and aggregate marginal costs

$$\frac{MC_t(j)}{P_t} = \frac{\left(P_t(j)/P_t\right)^{-\omega\theta}}{D_t}\frac{MC_t}{P_t},$$

where $\omega \equiv \eta^{-1}$, $MC_t / P_t \equiv (Y_t / A_t)^{\omega} D_t / [\Lambda_t A_t (1-\tau_{N,t})]$, and $D_t \equiv \int_0^1 \left(P_t(i)/P_t\right)^{-\omega\theta} di$ is a measure of the dispersion of prices across firms. We can then write a firm's instantaneous optimal desired relative price as

$$\left(\frac{P_t^{\#}}{P_t}\right)^{1+\omega\theta} = \left(\frac{\mu}{D_t}\right)\frac{MC_t}{P_t}, \tag{4}$$

Since there is no capital, government spending or international trade in the model, the goods market clearing condition is simply $Y_t = C_t$.

2.3 Price-Setting Behavior

Intermediate good producing firms are assumed to be in one of four price-setting sectors: sticky prices, sticky-information, rule-of-thumb, or flexible prices. Without loss of generality, firms of the same pricing sector are grouped into segments so that the price level can be written as

$$P_t = \left[\int_0^{s_1} P_t^{sp}(j)^{1-\theta} dj + \int_{s_1}^{s_2+s_1} P_t^{si}(j)^{1-\theta} dj + \int_{s_2+s_1}^{s_3+s_2+s_1} P_t^{rot}(j)^{1-\theta} dj + \int_{s_3+s_2+s_1}^{1} P_t^{flex}(j)^{1-\theta} dj\right]^{1/(1-\theta)},$$

where *sp, si, rot*, and *flex* are indices for sticky-price, sticky-information, rule-of-thumb, and flexible price firms respectively. Importantly, firms are otherwise identical in the sense that a firm in a given sector is the same competitor to all other firms symmetrically irrespective of whether they are in the same sector or not. The weighting parameters s_1, s_2, and s_3 are the fractions of firms that belong to the sticky-price, sticky-information, and rule-of-thumb sectors respectively. Flexible-price firms are assigned the remaining mass of s_4=1-s_1-s_2-s_3. Firms cannot switch sectors. Defining the price level specific to sector d as $P_t^d \equiv \left[s_d^{-1}\int_{s_{d-1}+s_{d-2}+\ldots}^{s_d+s_{d-1}+\ldots} P_t(j)^{1-\theta} dj\right]^{1/(1-\theta)}$ with s_0 = 0, we can rewrite the aggregate price level as

$$P_t = [s_1 (P_t^{sp})^{1-\theta} + s_2 (P_t^{si})^{1-\theta} + s_3 (P_t^{rot})^{1-\theta} + s_4 (P_t^{flex})^{1-\theta}]^{1/(1-\theta)} . \tag{5}$$

<u>Sticky price firms</u>: These firms face a constant probability $1-\delta_{sp}$ of being able to change their price each period. A firm with the ability to change its price at time t will choose a reset price B_t to maximize the expected present discounted value of future profits

$$B_t(j) = \arg\max_B \sum_{k=0}^{\infty} \delta_{sp}^k E_t \left\{ \Lambda_{t,t+k} \left(B - MC_{t+k}(j) \right) Y_{t+k}(j) \right\}$$

where $\Lambda_{t,t+k}$ is the nominal stochastic discount factor between times t and $t+k$ and firm-specific marginal costs and output are as before. Taking the first-order condition and replacing firm-specific marginal costs and output with their corresponding aggregate terms yields the optimality condition

$$\sum_{k=0}^{\infty} \delta_{sp}^k E_t \left\{ \Lambda_{t,t+k} Y_{t+k} P_{t+k}^{\theta} \left[B^{1+\omega\theta} - \mu MC_{t+k} P_{t+k}^{\theta\omega} / D_{t+k} \right] \right\} = 0 \tag{6}$$

so that all firms with the opportunity to reset prices choose the same value of B_t. The price level for sticky price firms obeys

$$P_t^{sp} = [(1-\delta_{sp}) B_t^{1-\theta} + \delta_{sp} P_{t-1}^{sp^{1-\theta}}]^{1/(1-\theta)} . \tag{7}$$

<u>Sticky-Information Firms:</u> These firms face a Poisson process for updating their information sets, with the probability of getting new information in each period given by $1-\delta_{si}$. In every period, firms set prices freely given their information set. The profit-maximization problem at time t for firm j which last updated its information set at time t-k is then

$$P_{t|t-k}^{si}(j) = \arg\max_P E_{t-k}[(P - MC_t(j)) Y_t(j)]$$

where firm-specific marginal costs and demand are determined as before. This yields the first-order condition that

$$E_{t-k} \left[\left(P/P_t \right)^{-\theta} Y_t \left(\left(P_t^{\#}/P \right)^{1+\omega\theta} - 1 \right) \right] = 0 \tag{8}$$

which implies that all sticky-information firms with the same information set will choose the same price. The price level for sticky information firms is

$$P_t^{si} = [(1-\delta_{si})\sum_{k=0}^{\infty} \delta_{si}^k (P_{t|t-k}^{si})^{1-\theta}]^{1/(1-\theta)} \tag{9}$$

To have a finite state space of the model, we will truncate the sum in equation (9) to only p lags where p is chosen sufficiently large to not affect our results.

Rule-of-Thumb Firms: These firms always change their prices by the previous period's inflation rate.[6] Hence, the price level for the rule-of-thumb sector follows

$$P_t^{rot} = P_{t-1}^{rot}(P_{t-1} / P_{t-2}). \tag{10}$$

Flexible Price/Information Firms: These firms are always free to change prices and have complete information. They thus always set prices equal to the instantaneously optimal price. The price level for flexible price firms is then just $P_t^{flex} = P_t^{\#}$.

2.4 Shocks

We assume the following shock processes. First, technology shocks follow a random walk with drift

$$\log A_t = \log a + \log A_{t-1} + \varepsilon_{a,t},$$

where $\varepsilon_{a,t}$ are independently distributed with mean zero and variance σ_a^2. Preference shocks follow a stationary AR(1) process

$$g_t = \rho_g g_{t-1} + \varepsilon_{g,t},$$

where $\varepsilon_{g,t}$ are independently distributed shocks with mean zero and variance σ_g^2.

2.5 Log-Linearizing around the Balanced-Growth Path

To ensure stationarity, we log-linearize the model around the balanced growth path in which Y_t/A_t is stationary. Note that equation (1) ensures that $\Lambda_t A_t$ is also stationary. Defining y_t and λ_t to be the log-deviations of Y_t/A_t and $\Lambda_t A_t$ from their balanced growth paths respectively, we can rewrite (1) in log-linearized form as

$$(1-\tfrac{h}{a})(1-\beta\tfrac{h}{a})\lambda_t = (1-\tfrac{h}{a})(1-\rho_g\beta\tfrac{h}{a})g_t + \tfrac{h}{a}(\beta E_t y_{t+1} + y_{t-1} - \varepsilon_{a,t}) - (1+\beta(\tfrac{h}{a})^2)y_t \qquad (11)$$

and the Euler equation as

$$\lambda_t = E_t\lambda_{t+1} + (r_t - E_t\pi_{t+1}), \qquad (12)$$

where $\pi_t \equiv \log(P_t/P_{t-1}) - \log(\overline{\pi})$ and $\overline{\pi} = P_t/P_{t-1}$ along the balanced growth path. The log-deviation of the interest rate r_t is defined as $r_t \equiv \log(R_t/\overline{R})$.

We allow the log of steady-state inflation to differ from zero, as in Cogley and Sbordone (2008). The log-deviation of inflation from its steady-state value is a weighted average of sector specific inflation rates

$$\pi_t = \sum_d s_d^{CPI}\pi_t^d \quad \text{for } d = \{1,2,3,4\}, \qquad (13)$$

where $\pi_t^d \equiv \log(P_t^d / P_{t-1}^d) - \log(\overline{\pi})$, $\overline{p^d} \equiv \overline{P^d / P}$ is the steady-state relative price level of sector j, and $s_d^{CPI} \equiv s_d\,\overline{p^d}^{1-\theta}$ is the effective share of sector d in the aggregate price index.

Because inflation is not zero on average, sticky-price firms have to take into account the fact that prices will tend to rise on average. From equation (6), we can find the steady-state relative reset price to be

$$\overline{(B/P)} = [(1-\gamma_1)/(1-\gamma_2)]^{1/(1+\omega\theta)}\,\overline{(P^\#/P)} > \overline{(P^\#/P)},$$

where $\gamma_1 \equiv \delta_{sp} a\overline{R}^{-1}\overline{\pi}^{\theta}$ and $\gamma_2 \equiv \delta_{sp} a\overline{R}^{-1}\overline{\pi}^{1+\theta(1+\omega)}$. But the non-zero rate of inflation also affects the steady-state level of the optimal relative price. Specifically, one can show that

$$\overline{\left(\frac{P^\#}{P}\right)} = \left[s_1\left(\frac{1-\delta_{sp}}{1-\delta_{sp}\overline{\pi}^{\theta-1}}\right)\left(\frac{1-\gamma_1}{1-\gamma_2}\right)^{\frac{(1-\theta)}{(1+\omega\theta)}} + \left(1-s_1\right)\right]^{1/(\theta-1)}.$$

To the extent that the extra weight attached to s_1 will in general not be equal to one, the optimal relative price will also then differ from one. In particular, when $\overline{\pi} > 1$, there exists a unique $\beta^*(\theta, \omega, \delta_{sp}, \overline{\pi})$ such that if $\beta > \beta^*$, the steady state average relative price level of sticky price firms is greater than one while the optimal relative price is less than one.[7] This is because when trend inflation is positive, the relative reset price chosen by sticky-price firms declines over time as the aggregate price level rises. If firms care enough about future profits, then they must choose a high reset price today to avoid the relative reset price being too low in the distant future. This will cause the average relative price level of sticky-price firms to be greater than one.

If the steady-state average relative price level of a sector d is greater than one, then its share in the final good will be lower than implied by its mass in the output index, that is, $s_d^{CPI} < s_d$. Consequently, price changes in this sector will have a smaller effect on aggregate inflation than would be the case if it had a steady-state relative price of one, as can be seen in equation (13). Because $\beta > \beta^*$ in all of our estimates, we have $s_1^{CPI} < s_1$.

From equation (4) and the definition of the real marginal cost, the log-linearized deviation of the instantaneously optimal relative price is given by

$$p_t^{\#} \equiv \log(P_t^{\#} / P_t) - \log(\overline{P^{\#} / P}) = (1 + \omega\theta)^{-1}(\omega y_t - \lambda_t). \tag{14}$$

Defining b_t as the log deviation of B_t / P_t from its stationary steady-state value and log-linearizing equation (6), expressed in stationary variables, around the balanced growth path leads to the following expression for the reset price[8]

$$b_t = (1-\gamma_2)\sum_{k=0}^{\infty}\gamma_2^k E_t p_{t+k}^{\#} + \frac{1}{1+\theta\omega}\sum_{k=1}^{\infty}(\gamma_2^k - \gamma_1^k)E_t[gy_{t+k} - r_{t+k-1}] + \frac{1}{1+\theta\omega}\sum_{k=1}^{\infty}[\gamma_2^k(1+\theta(1+\omega)) - \theta\gamma_1^k]E_t\pi_{t+k},$$

where $gy_t \equiv \log(Y_t / Y_{t-1}) - \log a$ is the log-deviation of the growth rate of output from its mean.

Denoting the log-deviation of the relative price level in sector d from its steady state value as $p_t^d \equiv \log(P_t^d / P_t) - \log(\overline{P_t^d / P_t})$, the log-linearized relative price level of sticky price firms follows

$$p_t^{sp} = (1-\delta_{sp})\overline{(b / p^{sp})}^{1-\theta} b_t + \delta_{sp}\bar{\pi}^{\theta-1}(p_{t-1}^{sp} - \pi_t),$$

where the steady-state ratio of reset prices to the sticky-price level is given by[9]

$$\overline{(b / p^{sp})} = [(1-\delta_{sp}) / (1-\delta_{sp}\bar{\pi}^{\theta-1})]^{1/(\theta-1)}.$$

For sticky-information firms, the log-linearized optimal relative price at time t conditional on information dated t-k is $p_{t|t-k}^{si} = E_{t-k} p_t^{\#}$ so the log-linearized relative price level for sticky-information firms can be expressed as

$$p_t^{si} = \delta_{si} p_{t-1}^{si} + (1-\delta_{si}) p_t^{\#} + (1-\delta_{si})\delta_{si}\sum_{k=0}^{\infty}\delta_{si}^k\left[(E_{t-1-k}\pi_t - \pi_t) + E_{t-1-k}\Delta p_t^{\#}\right]. \tag{16}$$

Since the inflation rate for rule-of-thumb firms is

$$\pi_t^{rot} = \pi_{t-1}, \tag{17}$$

the log-linearized relative price level of rule-of-thumb firms follows

$$p_t^{rot} = p_{t-1}^{rot} + \pi_{t-1} - \pi_t = p_{t-1}^{rot} - \Delta\pi_t. \tag{18}$$

Inflation of flexible-price full-information firms is

$$\pi_t^{flex} = p_t^{\#} - p_{t-1}^{\#} + \pi_t. \tag{19}$$

2.6 Central Bank

To close the model, we assume that the central bank sets interest rates according to a Taylor (1993) type rule with interest smoothing such that

$$r_t = (1-\rho_1-\rho_2)[\phi_\pi\pi_t + \phi_{gy} gy_t] + \rho_1 r_{t-1} + \rho_2 r_{t-2} + \varepsilon_{r,t}, \tag{20}$$

which allows the central bank to respond to inflation and the growth rate of output.[10] We include two lags of the interest rate in the right-hand side of (20) because in our previous work we document (e.g., Gorodnichenko and Shapiro 2007, Coibion and Gorodnichenko 2008a) that two lags appear to be the appropriate statistical description of serial correlation in the policy rule. The policy innovations $\varepsilon_{r,t}$ are assumed to be independently distributed with mean zero and variance σ_r^2.

3 Estimation Approach

Our log-linearized model has three variables that directly correspond to observable macroeconomic series: the inflation rate, the growth rate of output, and the nominal interest rate. The advantage of focusing on output growth, rather than the output gap as traditionally done, is that output growth is directly observable, whereas the output gap is not.[11] To estimate the underlying parameters of the model, we use a method-of-moments approach that seeks to match the contemporaneous and intertemporal covariances of the observable variables from the data to those of the model. After solving our model for the unique rational expectations equilibrium and letting Ψ denote the vector of parameters in the model, we can rewrite it in reduced form as

$$X_t = A(\Psi)X_{t-1} + B(\Psi)\Phi_t$$

with the measurement equation

$$Y_t = \Upsilon X_t + \Xi_t$$

where $\Phi_t \sim iid(0, \Sigma_\Phi(\Psi))$ is the vector of structural shocks, X_t is the vector of variables in the model, $Y_t = [gy_t \;\pi_t \;r_t]'$ is the vector of observable variables, Υ is the appropriate known fixed selection matrix, and $\Xi_t \sim iid(0, \Sigma_\Xi(\Psi))$ is the vector of serially and contemporaneously uncorrelated measurement errors with $\Sigma_\Xi = diag\{\sigma^2_{me,gy}, \sigma^2_{me,\pi}, \sigma^2_{me,r}\}$.[12]

Using this state-space representation of the model, we can extract the corresponding moments of the model for the observable variables and denote the resulting matrix with $\Delta_{Y,n}(\Psi) \equiv [vech(\Omega_{Y,0}(\Psi))' \; vec(\Omega_{Y,1}(\Psi))' \ldots vec(\Omega_{Y,n}(\Psi))']'$ where $\Omega_{Y,j} \equiv \text{cov}(Y_t, Y_{t-j})$ is the j^{th} autocovariance of Y_t. On the other hand, we can compute the sample autocovariance matrix for the observed variables, $\hat{\Delta}_{Y,n} \equiv [vech(\hat{\Omega}_{Y,0})' \;\; vec(\hat{\Omega}_{Y,1})' \;\; \dots \;\; vec(\hat{\Omega}_{Y,n})']'$ where $\hat{\Omega}_{Y,j}$ is the sample estimate of $\Omega_{Y,j}$ in the data. Our method of moments estimator of the parameters is then given by

$$\hat{\Psi} = \arg\min \left\{ (\Delta_{Y,n}(\Psi) - \hat{\Delta}_{Y,n})' \times W \times (\Delta_{Y,n}(\Psi) - \hat{\Delta}_{Y,n}) \right\}$$

where W is a weighting matrix. Following Abowd and Card (1989), Altonji and Segal (1996) and others, we use the identity weighting matrix in the estimation of the covariance structure.[13]

Most work on estimating DSGE models relies upon maximum likelihood or Bayesian approaches. We follow our alternative method-of-moments approach for several reasons. First, Ruge-Murcia (2007) compares method of moments estimators with other popular methods such as maximum likelihood for estimating DGSE models and finds that it performs well in simulations. Second, a particularly appealing feature of our method of moments approach is that the moments of the data used in the estimation have an economic interpretation. Comparing the predicted moments of the model to those of the data highlights which features of the data can and cannot be matched by the model. As we discuss in section 4.2.2, our method of moments estimator thus allows us to shed light on *why* the pure models are rejected in favor of the hybrid model. Thus, we interpret our empirical approach as one way to get inside the "black box" of estimated DSGE models.[14] Finally, we use simulation-based methods to estimate structural parameters without requiring the researcher to take a stand on priors. Our simulation-based method illustrates how medium and large scale models can be estimated within the classical statistical framework.

4 Results

We use U.S. data from 1984:Q1 until 2008:Q2.[15] The growth of output is measured as $400 \times log(RGDP_t/RGDP_{t-1})$ where *RGDP* is chained real gross domestic product. Inflation is measured using the Consumer Price Index by $400 \times log(P_t/P_{t-1})$. The interest rate is $400 \times log(1+R_t)$ where R_t is the Effective Federal Funds rate (at a quarterly rate). We focus on the contemporaneous covariances and the first three cross-autocovariances of these series to estimate the parameters of the model. We restrict the number of autocovariances to minimize the computational burden and to sharpen inference as the plethora of weakly informative moments tends to deteriorate the estimator's performance.[16]

Our model contains the following set of parameters $\Psi=\{a, \bar{R}, \bar{\pi}\ \beta, \eta, h, \theta, \delta_{si}, \delta_{sp}, s_1, s_2, s_3, \phi_\pi, \phi_{gy}, \rho_1, \rho_2, \rho_g, \sigma_r, \sigma_a, \sigma_{me,gy}, \sigma_{me,\pi}, \sigma_{me,r}\}$. We calibrate the balanced-growth inflation rate, interest rate, and growth rate of output to those observed in our sample: $\bar{\pi}=1.0077$, $a=1.0076$, $\bar{R}=1.0130$, and we impose $\beta = 0.99$ to guarantee that the consumer's problem is well bounded. We set $\eta = 1$, a fairly typical calibrated value for the Frisch labor supply elasticity, and set $\theta = 10$, such that the steady-state markup is about 11%. We experiment with alternative values of η and θ in robustness checks. We choose to calibrate these parameters rather than estimate them because these parameters have known identification problems. For example, Del Negro and Schorfheide (2008) and Canova and Sala (2009) report that standard monetary models have difficulties in distinguishing real (which is governed by η and θ) and nominal (which is governed by δ_{sp} and δ_{si}) rigidities. All other parameters are estimated using Markov Chain Monte Carlo (MCMC) methods, with details provided in the Appendix. We set the truncation of past expectations for the sticky information firms to $p = 12$. We restrict the degree of habit formation, the shares of firms, and the persistence of the preference shock to be between 0 and 1. Price and informational rigidities (δ_{sp} and δ_{si} respectively) are restricted to be between 0.3 and 0.95.[17]

4.1 Baseline Estimates

Table 1 presents our baseline estimates for the hybrid model, as well as estimation results for restricted models. For our baseline model, the degree of habit persistence, at 0.79, is well within the range of estimates found in other studies. Our Taylor rule estimates imply strong responses by the central bank to both inflation and the growth rate of output, with substantial inertia apparent in the interest rate. The weight assigned to sticky-price firms is 62%. Sticky-information firms receive a weight of 21%. Thus, sticky-prices and sticky-information jointly account for over 80% of firms in the model. Rule-of-thumb firms account for 9% of firms, while flexible price firms receive a share of eight percent. If we adjust the shares to reflect the fact that sticky-price firms charge higher prices on average than other sectors, the effective share of sticky-price firms falls to 59% while the effective share of sticky-information firms rises to 23%. The estimated degree of price rigidity δ_{sp} is 0.81, which implies that sticky-price firms update their prices every five quarters on average. Note that while this is higher than typical estimates of price rigidities (Bils and Klenow (2004) and Nakamura and Steinsson (2007)), the average price duration across all firms is on the order of three quarters, which is consistent with the literature. Sticky-information firms, with an estimated degree of informational rigidity of 0.95, update their information sets very infrequently, which is consistent with estimated degrees of informational rigidities in Khan and Zhu (2006) and Knotek (2009) over the post-1982 period.

Because no single firm type receives a share of 100%, the first implication of our results is that our nested model best matches the data when more than a single type of firm is present. However, sticky-price and sticky-information firms jointly account for most of the firms in the economy. To assess the relative importance of each type of firm, we consider restricted estimates of our models in Table 1. One version eliminates rule-of-thumb firms. The share of sticky-price firms rises to 63%, while that of sticky-information goes to 23% of firms. The model achieves only a slightly higher value of the objective function than the baseline case, indicating that rule-of-thumb firms contribute little to the ability of the model to match the data. When one eliminates sticky-information firms, on the other hand, the model fares worse in matching moments and we can reject this restriction at the 1% significance level. Thus, while rule-of-thumb firms do not appear to play a significant role in matching moments of the data, the sticky-information firms certainly do. Finally, we consider a specification in which both rule-of-thumb and flexible firms are set to zero. This version of the model yields a distribution of firms of about three-quarters sticky-price firms and one-quarter sticky-information firms and we cannot reject this restriction at 10% significance level.

Thus, the most striking result from our estimation is that *sticky-price and sticky-information firms play the most important role in matching the moments of the data*. When one accounts for these two types of firms, there is little need to allow for rule-of-thumb behavior or flexible-price full-information firms. This result is particularly noteworthy for two reasons. First, much of the literature on sticky-prices and sticky-information has focused on testing one model against the other (Korenok (2008), Kiley (2007b), Coibion (2010)). Our results imply instead that both are needed to match the moments of the data. Second, sticky-price models are commonly augmented with rule-of-thumb firms to introduce more inflation inertia (e.g., Gali and Gertler (1999)). However, when one allows for both rule-of-thumb and sticky-information firms, the data favors sticky information as a complement to sticky-price models.

4.2 How Does The Hybrid Model Differ From The Nested Pure Models?

In this section, we study why the data prefers a hybrid sticky-price sticky-information model over the pure models. First, we re-estimate the structural parameters of the model under the assumption that only one type of firm exists and construct variance decompositions for each estimated model. Second, we compare the predicted moments of the hybrid and pure models to those of the data. Third, we contrast the impulse response functions of each estimated model.

4.2.1 Estimates of Pure Models

To get a sense of how the hybrid model differs from pure models, we first re-estimate the parameters while imposing that the model be entirely composed of sticky-price, sticky-information, or flexible-price full-information firms. The results are presented in Table 2. Note first that the sticky-price model achieves the lowest value of the objective function after the hybrid model, the sticky-information model comes second, while the flexible-price model does much worse. For all three restricted models, p-values for the restrictions imposed by these models are less than or equal to 5%. In addition, there are some notable differences in estimated parameters across models. The sticky-price model points to somewhat stronger responses by the Fed to inflation and output growth than in the hybrid model while the sticky information model yields a much larger response to output growth but a smaller response to inflation. For estimated shock processes, the biggest difference is that the standard deviation of technology shocks is much lower in the sticky-information model than in other models.

The differences in the estimates have important implications for the relative importance attributed to each shock in explaining macroeconomic dynamics. Table 3 presents the one-year ahead variance decompositions of output growth, inflation, and interest rates due to structural shocks in each model.[18] For output growth, all of the models yield the conclusion that most of the variance is due to preference shocks. For inflation, there is much more variation across models. The hybrid and sticky-price models attribute much of the variance of inflation to technology and preference shocks. The sticky-information and flexible models, on the other hand, both attribute much more importance to monetary policy innovations. With respect to interest rate fluctuations, all of the models attribute much of the variation to preference shocks, although the sticky information model again attributes some role (25%) to monetary policy innovations while the flexible model assigns a sizable weight to technology shocks. Overall, the sticky-price model yields a variance decomposition of macroeconomic variables that closely mirrors that of the hybrid model, with preference shocks being most important but with technology shocks playing a key role in explaining inflation. The sticky-information model places little weight on technology shocks, and instead assigns a much larger role to monetary policy innovations.

4.2.2 Comparing Predicted Moments

To further contrast the pure and hybrid models, we consider which features of the data each model can match. Figure 1 presents the autocovariances of the observable variables implied by the models and those found in the data, as well as 95% confidence intervals derived from a non-parametric bootstrap.[19] First and most dramatically, the flexible price model is unable to reproduce the high autocovariance of interest rates and output growth rate observed in the data. Second, all other models adequately reproduce the autocorrelation of output growth and interest rates, largely because this is driven by the estimates of internal habit formation and high interest rate smoothing in the central bank's reaction function. Third, the sticky-information model tends to somewhat overstate the persistence of inflation.

Figure 2 presents the cross-covariances of inflation with respect to leads and lags of output growth and interest rates, as well as that of output growth to leads and lags of interest rates. The moments of the data indicate that inflation leads output growth and interest rates, such that high inflation today is associated with higher interest rates and lower output growth in subsequent quarters. In addition, output growth leads interest rates. The fully flexible model is largely incapable of reproducing these lead-lag characteristics of the data. The sticky-information model has difficulty reproducing the fact that inflation leads output growth and interest rates: in the case of output growth, the sticky-information model predicts that the highest covariance (in absolute value) is contemporaneous while in the case of interest rates, the sticky-information model predicts that inflation should lag interest rates. The sticky-price model, on the other hand, replicates these lead-lag patterns more precisely. This reflects the forward-looking behavior embodied in the reset-price decisions of sticky-price firms. The hybrid model, overall, yields dynamics that are very similar to the sticky-price model.

4.2.3 Impulse Responses

To understand why the sticky-information model places more weight on monetary policy shocks but less weight on technology than either the hybrid or pure sticky-price model, we consider in Figure 3 the impulse responses of the observable variables to one-unit shocks in the estimated hybrid, sticky-price and sticky-information models.[20]

Consider first the effects of preference shocks, since these shocks account for the brunt of the variance decomposition of macroeconomic variables across models. In response to preference shocks, output growth jumps up and returns monotonically back to zero over time. This response is similar across models and is driven by the estimated habit formation parameter and the persistence of the shock. The rapid decline in output growth helps match the autocorrelation function of output growth for all models. The gradual increase in the interest rate helps replicate the observation that output growth leads interest rates in the data. Because inflation is positive after this shock (albeit with a lag for sticky-information), this shock can also help replicate the positive correlation between inflation and interest rates observed in the data. However, it cannot explain the contemporaneous negative correlation between inflation and output growth. For the sticky-information model, the delayed response of inflation to the preference shock causes inflation to lag output growth and interest rates, a result at odds with the data.

Turning to technology shocks, the key finding for sticky price and hybrid models are the contemporaneous decrease in inflation and increase in output growth. This response allows these two models to replicate the unconditional negative correlation between inflation and output growth observed in the data. In addition, because inflation jumps down on impact and returns rapidly to the steady-state while output growth converges only slowly after this permanent shock, this shock allows the sticky-price and hybrid models to replicate the finding that inflation leads output growth. This accounts for the substantial weight assigned to this shock by the sticky-price and hybrid models in accounting for inflation dynamics. For the sticky-information model, the permanent nature of the technology shock yields a very delayed response of inflation, which again tends to counterfactually imply that inflation lags output growth.

In response to monetary policy shocks, the increase in the interest rate leads to a decrease in output growth and inflation across models. Since this tends to imply a negative correlation between output growth and interest rates, as well as between inflation and interest rates, the sticky-price and hybrid models assign almost no weight to this shock, as the key lead-lag relationships are already accounted for by the preference and technology shocks. However, we can see from this impulse response why monetary policy shocks play such an important role for the sticky-information model. Note that inflation declines for a number of quarters after a monetary policy shock under the sticky-information model, a point emphasized by Mankiw and Reis (2002). The interest rate, on the other hand, peaks in the second quarter then returns monotonically back to zero. Thus, after the first period, the correlation between inflation and the interest rate is positive in the sticky information model as inflation and interest rates decline simultaneously. In addition, because inflation falls in the first period while the interest rate only starts to decline in the second period, this shock helps deliver a lead of inflation over interest rates, which was the feature of the data that the sticky-information model could not match with preference and technology shocks.

4.3 How Important Is Strategic Interaction Among Different Price-Setting Firms?

To see how the behavior of firms within the hybrid model compares to their behavior when they are the only type of firm, we plot in Figure 4 the response of inflation in each sector to structural shocks, as well as the response of aggregate inflation in a model consisting only of this type of firm. For the latter, we use the estimated parameters of the hybrid model and simply alter the share of firms to isolate the strategic interaction effect.[21]

Focusing first on sticky-price firms, in response to monetary policy, technology, and preference shocks, inflation among sticky-price firms within a hybrid model is substantially dampened (by about 30% on impact) relative to what it would have been had these been the only type of firm in the model. For sticky-information firms, the effect is reversed: their inflation response is more rapid within the hybrid model than in a pure sticky-information model. This is strategic complementarity at work: the resulting inflation responses in each sector are much more similar than the inflation responses of the pure models. The effect of strategic complementarity is even more striking in the case of flexible-price full-information firms. Whereas inflation for these firms would be substantial on impact—but virtually nil in subsequent periods—within the hybrid model their inflation response is severely dampened. This reflects how much more sensitive these firms are to the behavior of other firms because they are unconstrained in their actions whereas all other firms face some kind of constraint, which is similar in spirit to Haltiwanger and Waldman (1991). In the bottom row of Figure 4 we contrast the dynamics of aggregate inflation in the hybrid model and the dynamics of the weighted sum of inflation in the pure models. We interpret the weighted sum dynamics as a case where consumers have a two-tier utility function with very low elasticity of substitution across sectors and θ=10 elasticity of substitution within sectors.[22] The hybrid model exhibits more gradual and persistent dynamics than the weighted sum over pure models thus suggesting that ignoring strategic interaction between firms with different price setting may considerably distort the aggregate dynamics.

To assess more formally the quantitative importance of strategic interaction in price setting across sectors, we re-estimate all of the parameters of our model but applied to a weighted sum of sector-specific models ("weighted model"). In other words, for a given set of parameters, we feed these parameters into three separate economies where each economy is characterized by a single price setting type (sticky-price, sticky-information, and flexible-price full-information) and use a weighted sum of these economies to construct the aggregates, from which we construct the predicted moments for the weighted model.[23] Although the estimates are broadly similar to our baseline results, we find that the share of sticky price firms falls while the share of sticky-information firms increases so that each type constitutes approximately 50% (see Table 2). However, the fit of the weighted model is considerably worse than the fit of the baseline model. Based on tests of the over-identifying restrictions, we can reject the validity of the weighted model but not that of the baseline model at any standard significance level. This result illustrates that strategic interaction across sectors within the hybrid model is a key element to match the data.

4.4 Robustness Analysis

In this section, we consider the robustness of our estimates to several potential issues. The first issue we address is the set of moments used in the estimation. Our baseline results relied on the autocorrelations of our observable variables over three quarters and dynamic cross-correlations at maximum leads and lags of three quarters as well. The purpose of focusing on such a restricted set of moments was to concentrate on those moments that are most precisely estimated. As a robustness check, we consider the use of a larger set of moments, specifically using autocovariances over two years, and report results in Table 4. Most of the parameters are similar to baseline estimates. The estimated levels of price and informational rigidities are almost identical to our baseline estimates and the estimated shares of firms continue to imply that more than 80% of firms are sticky-price or sticky-information firms.

An alternative approach to dealing with the precision of the moments used in the estimation is to allow for a non-identity weighting matrix. Although the optimal weighting matrix would seem an ideal candidate, many studies report poor performance of this weighting matrix in applications (e.g., Boivin and Giannoni 2006) and Monte Carlo simulations (e.g., Altonji and Segal (1996)) that involve estimation of covariance structures.[24] A practical compromise is a diagonal weighting matrix with estimated variances of the moments on the diagonal and zeros for off-diagonal entries. Replicating our baseline estimation procedure with the diagonal weighting matrix, we find that sticky-price firms account for approximately fifty percent of firms, while rule-of-thumb and sticky-information firms account for 18% and 16% respectively. Essentially, the use of the diagonal weight matrix downplays some informative moments and does not allow us to clearly separate rule-of-thumb and sticky-information firms. Most other parameter estimates are broadly similar to the estimates based on the identity weight matrix.

We also consider sensitivity to the elasticity of labor supply. While most empirical work has found low elasticities of labor supply, some of the RBC literature has focused on the case with infinite labor supply (as in Hansen (1985)). In Table 4, we present estimates of the hybrid model under the assumption of indivisible labor ($\eta = \infty$), which implies that $\omega = 0$ so that there is no strategic complementarity in price setting although (in contrast to the weighted model) there is some interaction via aggregate demand. Eliminating strategic complementary has a dramatic effect on the results. Specifically, the shares of sticky-information and flexible price firms both go to zero, while that of rule-of-thumb firms rises to 50%. This change in outcome leads to a substantial deterioration in the model's ability to match the data and we can reject the model at any standard significance level using tests of the over-identifying restrictions. The reduced share of sticky-information firms reflects the fact that, in the absence of strategic complementarity in price setting, sticky-information firms fail to produce inflation inertia. Because sticky-price firms tend to induce excessive forward-looking behavior in inflation, the model needs other types of firms to slow down the adjustment of inflation to shocks. With sticky-information firms unable to achieve this role in the absence of strategic complementarity, the estimation instead places a significant weight on rule-of-thumb firms.

As a check, we explore the effects of using alternative policy reaction functions. First, we consider the following Taylor rule $r_t = (1-\rho_1-\rho_2)[\phi_\pi \pi_t + \phi_{gy} gy_t + \phi_x x_t] + \rho_1 r_{t-1} + \rho_2 r_{t-2} + \varepsilon_{r,t}$ where x_t

is the log-deviation between actual output and the level of output that would occur in the absence of price and informational rigidities. The estimated response to the output gap is very low and not statistically different from zero while the other parameters are largely unchanged. Second, we integrate the following Taylor rule into our model $r_t = (1-\rho_1)[\phi_\pi \pi_t + \phi_{gy} gy_t] + \rho_1 r_{t-1} + \varepsilon_{r,t}$ which restricts interest smoothing to be an AR(1) process. With this restriction, the main results are broadly unchanged, with sticky-price firms accounting for 60% of firms and sticky-information firms accounting for 15%. The share of flexible-price firms rises to 16%. However, we can reject imposing an AR(1) specification at the 5% significance level.

The estimated degree of information rigidity δ_{si} implies that firms update their information sets infrequently. Although the estimate of δ_{si} is consistent with previous studies, a large value of δ_{si} may imply that the results are sensitive to the truncation lag p. To verify that our results are insensitive to the choice of p = 12, we re-estimate the model with p = 24 and find very similar results, as illustrated in Table 4. In particular, the estimated degree of information rigidity and the share of sticky information firms are unchanged.

Our final robustness check is with respect to the elasticity of substitution across intermediate goods θ. We fixed this parameter in our baseline estimation because previous work has shown that it is difficult to differentiate empirically between nominal and real rigidities, making the joint identification of θ and the shares of firms tenuous. To assess how sensitive our results are to θ, we redid our baseline estimation procedure for values of θ ranging from 7 to 15. Our results for the key parameters of interest, shares of firms and the degree of price and information rigidities, are in Figure 5. In Panel A, we can see that lower values of θ have a substantial effect on estimated shares of firms. Specifically, the share of sticky-information firms declines rapidly while that of sticky-price firms rises. As lower values of θ reduce strategic complementarity in price setting, we get higher estimates of price rigidity to keep the persistence of inflation high (Panel B). However, the fit of the model worsens substantially as strategic complementarity decreases moderately (Panel C). With higher values of θ, on the other hand, the estimated shares of firms are very similar to our baseline estimates under the assumption of θ = 10. As θ rises, the degree of strategic complementarity increases (i.e., $(1+\omega)/(1+\omega\theta)$ decreases and prices become less sensitive to changes in output; see Panel D), as does the inherent persistence of inflation, and hence we obtain lower estimates of price rigidity. The fit of the model actually improves with higher values of θ, indicating that even more strategic complementarity is desirable to match the data. Thus, one could interpret our baseline results as a *lower bound* on the importance of strategic complementarity in price setting across heterogeneous price-setting firms.

5 Implications for Optimal Monetary Policy

The presence of different types of firms in the model raises the issue of what kind of monetary policy is optimal in such a setting. To assess the effect of different policies, we follow much of the literature and assume that the central banker has the following loss function

$$L_1 = \text{var}(\pi_t) + \omega_y \text{var}(x_t) + \omega_r \text{var}(r_t), \tag{21}$$

where ω_y and ω_r show the weight on output gap and interest rate volatility relative to inflation volatility so that the variability in the output gap (and later the output growth rate) and the interest rate are converted to their inflation-variance equivalents. We also consider an alternative loss function which penalizes the volatility of output growth instead of the volatility of the output gap:

$$L_2 = \text{var}(\pi_t) + \omega_y \text{var}(gy_t) + \omega_r \text{var}(r_t), \tag{22}$$

This alternative loss function may be interesting for our analysis because, as Amato and Laubach (2004) show, habit formation introduces a concern for the volatility in the change of consumption and, hence, the loss function should include a term that captures the volatility of output growth.

In principle, the parameter ω_y can be derived from the Phillips curve. However, because we have different interacting price-setting mechanisms as well as non-zero steady state inflation, we could not find a closed-form solution for the Phillips curve and ω_y, so objective functions (21) and (22) are not necessarily model consistent for welfare calculations. Consequently, we are agnostic about the relative weight of output gap variability and we experiment with different values of ω_y. In the baseline scenario, we set $\omega_y = 1$. The last term in the loss function is the penalty for the volatility of the policy instrument (interest rate) which helps to keep the optimal responses to output growth and inflation bounded. We follow Woodford (2003) and calibrate $\omega_r = 0.077$.

We constrain our analysis to simple rules with fixed coefficients (i.e. under commitment) similar to the estimated interest rate rule (20) for reasons highlighted in Williams (2003). First, simple rules can often closely approximate fully optimal rules. Second, simple rules tend to be more robust. Third, with many sectors and the complicated structure of the model, we could not find a closed form solution of the objective function and hence could not derive fully optimal rules.

The first question we pose is whether the central bank could have achieved lower losses by responding differently to aggregate inflation and output growth than what is implied by our estimates of the Taylor rule. In the exercise, we assume that the estimated shares of firms, the degrees of nominal and informational rigidities and other estimated parameters do not change with the policy rule. Panel A in Figure 6 presents the isoloss maps for different combinations of ϕ_π and ϕ_{gy} in the Taylor rule. Generally, there are substantial gains from increasing the response to inflation which reduces the volatility of inflation, the interest rate and the output gap. Holding everything else constant, a more aggressive response to inflation decreases the volatility of inflation, the interest rate, and the output gap and weakly increases the volatility of output growth. In contrast, a stronger response to the output growth rate has the opposite effect on the volatility of relevant macroeconomic variables. Since the volatility of output growth is fairly insensitive to changes in ϕ_π and ϕ_{gy} in the

Taylor rule, social welfare generally improves with larger ϕ_π and somewhat smaller ϕ_{gy} irrespective of what values we use for ω_y in the loss functions.

The second question we ask is whether the optimal policies in pure sticky-price and sticky-information models are similar to those found in the hybrid model. In particular, one may be concerned that using pure models to design policy rules can misguide the policymaker about his or her tradeoffs. Because scales of the social loss maps vary across models, we compute isoloss maps for pure sticky price (PSP) and pure sticky information (PSI) models and normalize these maps by the corresponding values of the loss function evaluated at the estimated Taylor rule parameters. These rescaled isoloss maps, which we call relative welfare maps, can be interpreted as losses relative to the loss incurred when the policymaker uses the estimated Taylor rule. We also scale the isoloss map for the hybrid model and then divide the relative welfare for the PSP and PSI models by the relative welfare map for the hybrid model. In summary, we consider maps

$$\left[\frac{L_k^{PSP}(\phi_\pi,\phi_{gy})/L_k^{PSP}(\hat{\phi}_\pi,\hat{\phi}_{gy})}{L_k^{HYBR}(\phi_\pi,\phi_{gy})/L_k^{HYBR}(\hat{\phi}_\pi,\hat{\phi}_{gy})}\right] \text{ and } \left[\frac{L_k^{PSI}(\phi_\pi,\phi_{gy})/L_k^{PSI}(\hat{\phi}_\pi,\hat{\phi}_{gy})}{L_k^{HYBR}(\phi_\pi,\phi_{gy})/L_k^{HYBR}(\hat{\phi}_\pi,\hat{\phi}_{gy})}\right],\ k=1,2, \tag{23}$$

where $(\hat{\phi}_\pi,\hat{\phi}_{gy})$ are the estimated values of the policy reaction function reported in Table 1.

The resulting maps (23) show to what extent using PSP and PSI models misinforms the policymaker about tradeoffs relative to the hybrid model.[25] Specifically, if the ratio of relative welfare maps for PSP or PSI to the relative welfare map for the hybrid model is close to one uniformly in (ϕ_π,ϕ_{gy}) space, there is no distortion in the tradeoffs. If the ratio is greater than one (smaller than one) with deviations of (ϕ_π,ϕ_{gy}) from $(\hat{\phi}_\pi,\hat{\phi}_{gy})$, then using the PSP or PSI model understates (overstates) the gain in welfare. Panels B and C in Figure 6 show the ratio of relative welfare maps (23) for PSP and PSI models respectively. These maps demonstrate that using pure models instead of the hybrid model can mislead the policymaker about potential gains from using alternative policy rules. For example, when the policymaker uses the PSI model to design policy, he or she underestimates the benefits from stronger responses to inflation relative to gains implied by the hybrid model because the ratio of relative welfare maps rapidly falls as ϕ_π increases. Hence, we conclude that using pure models can provide a distorted picture of tradeoffs actually faced when price-setting is heterogeneous.

Given that PSP and PSI models have different implications for whether the central bank should target the price level or inflation, the third question we ask is whether our hybrid model predicts an important role for price level targeting. To answer this, we augment the Taylor rule with a term that corresponds to price level targeting (PLT):

$$r_t = (1-\rho_{1,r}-\rho_{2,r})\phi_\pi \pi_t + (1-\rho_{1,r}-\rho_{2,r})\phi_{PLT} p_t + (1-\rho_{1,r}-\rho_{2,r})\phi_{gy} gy_t + \rho_{1,r} r_{t-1} + \rho_{2,r} r_{t-2} + \varepsilon_{r,t},$$

where p_t is the price level linearized around $p_t^* = p_0 \bar{\pi}^t$. In this exercise, we fix ϕ_{gy} at the estimated value, vary ϕ_π and ϕ_{PLT} and plot the resulting isoloss maps in Panel D of Figure 6. In general, there are significant welfare gains from having an element of PLT in the Taylor rule. In fact, even small positive responses to deviations from the price level target dramatically reduce the volatility of the output gap, the interest rate and inflation. At the same time, similar to the inflation response, a more aggressive PLT response tends to weakly increase the volatility of output growth. However, because this increase is very small, the changes in welfare are strongly dominated by declines in $\mathrm{var}(x_t)$, $\mathrm{var}(\pi_t)$, and $\mathrm{var}(i_t)$ so that PLT is generally desirable for all reasonable values of ω_y. Importantly, introducing PLT eliminates a region of equilibrium indeterminacy (compare with Panel A, Figure 6) and therefore PLT could reduce the volatility of macroeconomic variables in other ways.

Finally, having the central bank respond to aggregate inflation imposes the restriction that a one percent increase in inflation in a sector leads to an increase in the interest rate proportional to that sector's effective share of inflation dynamics, as defined in equation (20). The fourth question we ask is whether there are gains to be had by responding differently to inflation in each sector. For this purpose, we compute optimal policy rules using

$$\begin{aligned} r_t &= (1-\rho_{1,r}-\rho_{2,r})\phi_\pi^{(SP)}\pi_t^{(SP)} + (1-\rho_{1,r}-\rho_{2,r})\phi_\pi^{(SI+ROT+FLEX)}\pi_t^{(SI+ROT+FLEX)} \\ &\quad +(1-\rho_{1,r}-\rho_{2,r})\phi_{gy} gy_t + \rho_{1,r} r_{t-1} + \rho_{2,r} r_{t-2} + \varepsilon_{r,t}, \end{aligned}$$

where we assume that the central banker can differentiate between sectors that have prices fixed for some time (*SP*) and those that have prices changing every period (*SI*, *ROT* and *FLEX*). Here, we again fix ϕ_{gy} at the estimated value, vary $\phi_\pi^{(SP)}$ and $\phi_\pi^{(SI+ROT+FLEX)}$ and plot the resulting isoloss maps in Panel E of Figure 6.[26] We find a striking result: the isoloss maps are approximately linear in $\phi_\pi^{(SP)}$ and $\phi_\pi^{(SI+ROT+FLEX)}$ in the neighborhood of the estimated response to inflation. Hence, the policymaker does not face an increasing marginal penalty for targeting only one of the sectors. In addition, we find that only responding to inflation in the sticky-price sector is generally more stabilizing than only responding to inflation in the other sectors, which is consistent with Aoki (2001) and with the notion that sticky-price firms play a disproportionally large role in governing inflation dynamics through strategic complementarity in pricing setting, see section 4.3. At the same time, the policymaker can generally achieve a lower level of social loss by having a less aggressive response to inflation when he or she targets inflation in all sectors rather than in just one sector.

6 Conclusion

Empirical work has documented a striking amount of heterogeneity in pricing practices: both in the frequency at which firms update prices as well as in the source of costs underlying firm decision-making processes. We present a model in which four commonly used representations of how firms set prices are allowed to coexist and interact via their price-setting decisions. This model nests many specifications previously considered in the literature. We find that the two most important types of price-setting behavior are described by sticky prices and sticky information while rule-of-thumb and flexible pricing are quantitatively unimportant. This finding suggests that sticky-information firms may be more important than previously thought.

In addition, because the dynamic cross-covariances reveal important insights about the lead-lag structure of economic relationships, we can provide intuitive explanations for how the hybrid model outperforms pure sticky-price or sticky-information models. For example, we argue that a pure sticky information model tends to under-predict the degree of forward-looking behavior in inflation. In contrast, previous work that emphasized the time series representation of the data could not readily provide an economic rationale for why one model is preferred to others.

Heterogeneity in price-setting poses important issues for policymakers. We demonstrate that focusing on models with a single price-setting mechanism can misinform central bankers about trade-offs they face. Our simulations suggest that a more aggressive response to inflation, which may include an element of price level targeting, could substantially improve social welfare functions. At the same time, we do not find large benefits from targeting sectors with some particular form of price setting so that targeting aggregate inflation is a reasonable strategy.

While we focus on the possibility of important differences in how firms set prices, this approach could be naturally extended to wage-setting decisions. Christiano et al (2005), for example, argue that sticky wages with indexation are a particularly important element in matching macroeconomic dynamics. Yet, as with prices, allowing for indexation cannot reproduce the fact that wages often do not change for extended periods of time. A more natural approach could be to allow for heterogeneity in wage-setting assumptions for different sectors of the economy to capture the fact that some sectors have highly flexible wages, others have sticky wages without indexation, and some sectors, particularly those under union contracts, choose time paths for future wages infrequently. Even with small sticky-wage or union-wage sectors, the behavior of the flexible-wage sector could be substantially altered if there is strategic complementarity in wage setting.

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APPENDIX: Technical Details on Estimation

To estimate models, we use a Markov Chain Monte Carlo (MCMC) method developed in Chernozhukov and Hong (2003; henceforth CH). We employ the Hastings-Metropolis algorithm to implement CH's estimation method. Specifically our procedure to construct chains of length N can be summarized as follows:

Step 1: Draw $\Theta^{(n)}$, a candidate vector of parameter values for the chain's n+1 state, as

$\Theta^{(n)} = \Psi^{(n)} + \psi^{(n)}$ where $\Psi^{(n)}$ is the current n state of the vector of parameter values in the chain, $\psi^{(n)}$ is a vector of i.i.d. shocks taken from $N(0, \Omega_{\psi})$, Ω_{ψ} is a diagonal matrix.

Step 2: Take the n+1 state of the chain as

$$\Psi^{(n+1)} = \begin{cases} \Theta^{(n)} \text{ with probability } \min\{1, \exp[J(\Psi^{(n)}) - J(\Theta^{(n)})]\} \\ \Psi^{(n)} \text{ otherwise} \end{cases}$$

where $J(\Psi^{(n)})$ is the value of the objective function at the current state of the chain and $J(\Theta^{(n)})$ is the value of the objective function using the candidate vector of parameter values.

The initial Ω_{ψ} is calibrated to about one percent of the parameter value and then adjusted on the fly for the first 100,000 draws to generate 0.3 acceptance rates of candidate draws, as proposed in Gelman et al (2004).

CH show that $\bar{\Psi} = \frac{1}{N}\sum_{n=1}^{N}\Psi^{(n)}$ is a consistent estimate of Ψ under standard regularity assumptions of GMM estimators. CH also prove that the covariance matrix of the estimate of Ψ is given by $T^{-1}V\Omega V$ where $\Omega = DW\Gamma WD'$, W in the weighting matrix, D is the Jacobian of the moment conditions, T is sample size, Γ is the covariance of moment conditions, and $V = \frac{1}{N}\sum_{n=1}^{N}(\Psi^{(n)} - \bar{\Psi})^2 = \text{var}(\Psi^{(n)})$. Note that if W is the optimal weight matrix, then the covariance matrix is given by V. Given the short samples and highly nonlinear optimization, we employ bootstrap-based standard errors which we find to have better coverage rates. Our bootstrap procedure can be summarized as follows: a) we estimate a VAR; b) resample the residuals; c) construct new series using the resampled residuals and estimated VAR; d) estimate the parameters on newly created data; e) repeat steps b)-d) many times; f) compute standard errors based on bootstrap replications. We found in simulations that this procedure has superior statistical properties.

We use 500,000 draws for our baseline and robustness estimates, and drop the first 100,000 draws ("burn-in" period). We run a series of diagnostics to check the properties of the resulting distributions from the generated chains. We find that the simulated chains converge to stationary distributions and that simulated parameter values are consistent with good identification of parameters. More details are available in Coibion and Gorodnichenko (2008b).

Table 1: Estimation Results

	Hybrid Model		No ROT Firms		No SI Firms		Only SP and SI	
	estimate	(s.e.)	estimate	(s.e.)	estimate	(s.e.)	estimate	(s.e.)
Fundamentals								
Labor Supply Elasticity (η)	1		1		1		1	
Elasticity of Substitution across Goods (θ)	10		10		10		10	
Habit formation (h)	0.79	(0.09)	0.80	(0.16)	0.75	(0.23)	0.77	(0.16)
Taylor Rule								
Inflation Response (ϕ_π)	2.80	(0.66)	3.15	(0.93)	3.30	(0.92)	2.92	(0.84)
Output Growth Response (ϕ_{gy})	2.61	(0.77)	3.38	(1.18)	2.45	(1.06)	2.88	(0.97)
Interest Smoothing (ρ_1)	1.52	(0.09)	1.33	(0.15)	1.32	(0.28)	1.46	(0.16)
Interest Smoothing (ρ_2)	-0.59	(0.08)	-0.40	(0.13)	-0.42	(0.21)	-0.53	(0.14)
Price-Setting								
Sticky-Price Sector (s_1)	0.62	(0.12)	0.63	(0.15)	0.66	(0.22)	0.75	(0.13)
Sticky-Information Sector (s_2)	0.21	(0.10)	0.23	(0.11)	0.00		0.25	(0.13)
Rule-of-Thumb Sector (s_3)	0.09	(0.06)	0.00		0.32	(0.18)	0.00	
Price Rigidity (δ_{sp})	0.81	(0.07)	0.81	(0.08)	0.80	(0.14)	0.80	(0.10)
Information Rigidity (δ_{si})	0.95	(0.13)	0.95	(0.13)	0.75		0.95	(0.14)
Shocks								
Persistence Preference Shock (ρ_q)	0.85	(0.15)	0.88	(0.13)	0.87	(0.12)	0.87	(0.12)
Standard Deviation: Policy Shocks (σ_r)	0.21	(0.05)	0.25	(0.12)	0.30	(0.21)	0.23	(0.10)
Standard Deviation: Preference Shocks (σ_q)	9.26	(3.19)	10.33	(3.06)	9.33	(3.70)	9.54	(3.06)
Standard Deviation: Technology Shocks (σ_a)	3.26	(1.35)	2.92	(1.12)	2.84	(1.45)	3.20	(1.09)
Measurement Error								
Standard Deviation: Output Growth ($\sigma_{me,gy}$)	1.44	(0.38)	1.47	(0.31)	1.43	(0.52)	1.44	(0.31)
Standard Deviation: Inflation ($\sigma_{me,\pi}$)	1.23	(0.12)	1.22	(0.16)	1.27	(0.34)	1.22	(0.14)
Standard Deviation: Interest Rate ($\sigma_{me,r}$)	0.09	(0.07)	0.11	(0.07)	0.09	(0.07)	0.10	(0.05)
Value of Objective Function	51.2		52.4		59.0		52.3	
Minimum χ^2 statistic	22.49		25.33		39.48		25.03	
p-value DD test	-		0.19		0.01		0.23	

Note: The table presents estimates of the baseline model, using a truncation of past expectations for sticky-information firms of p=12, as well as estimates of restricted models. We use contemporaneous covariances and cross-autocovariances up to three lags. Data are from 1984:Q1 to 2008:Q2. Standard errors are constructed using non-parametric bootstrap. Bootstraps are done by running a 4-lag VAR on our data, and using the VAR coefficients and residuals to generate 2000 replications of the data which are used to re-estimate the model in each bootstrap replication. Minimum χ^2 statistic is computed as in Newey (1985). *P-value DD test* is the simulated probability value for the distance difference test (based on the difference in minimum χ^2 statistics) of imposed restrictions. See text and appendix for details on estimation approach.

Table 2: Estimates of the Pure Models

	Sticky-Price Model		Sticky-Info Model		Flexible Price Model		Weighted model	
	estimate	(s.e.)	estimate	(s.e.)	estimate	(s.e.)	estimate	(s.e.)
Fundamentals								
Labor Supply Elasticity (η)	1		1		1		1	
Elasticity of Substitution across Goods (θ)	10		10		10		10	
Habit formation (h)	0.69	(0.21)	0.82		1.00	(0.03)	0.71	(0.11)
Taylor Rule								
Inflation Response (ϕ_π)	3.46	(0.92)	1.70	(0.85)	1.74	(0.71)	3.35	(1.00)
Output Growth Response (ϕ_{gy})	2.44	(1.19)	4.52	(1.31)	0.76	(0.44)	1.89	(0.64)
Interest Smoothing (ρ_1)	1.29	(0.22)	1.45	(0.14)	1.15	(0.46)	1.44	(0.17)
Interest Smoothing (ρ_2)	-0.39	(0.19)	-0.50	(0.14)	-0.67	(0.24)	-0.55	(0.13)
Price-Setting								
Sticky-Price Sector (s_1)	1.00		0.00		0.00		0.53	(0.14)
Sticky-Information Sector (s_2)	0.00		1.00		0.00		0.45	(0.12)
Rule-of-Thumb Sector (s_3)	0.00		0.00		0.00		0.00	
Price Rigidity (δ_{sp})	0.80	(0.09)					0.84	(0.07)
Information Rigidity (δ_{si})			0.90	(0.07)			0.48	(0.17)
Shocks								
Persistence Preference Shock (ρ_g)	0.88	(0.11)	0.86	(0.14)	1.00	(0.28)	0.86	(0.08)
Standard Deviation: Policy Shocks (σ_r)	0.27	(0.17)	0.34	(0.15)	0.29	(0.20)	0.14	(0.06)
Standard Deviation: Preference Shocks (σ_g)	9.54	(3.08)	9.29	(4.25)	9.87	(4.68)	8.79	(3.08)
Standard Deviation: Technology Shocks (σ_a)	3.05	(1.27)	0.57	(0.42)	3.54	(1.65)	3.47	(1.45)
Measurement Error								
Standard Deviation: Output Growth ($\sigma_{me,gy}$)	1.37	(0.43)	1.44	(0.40)	1.91	(0.25)	1.39	(0.43)
Standard Deviation: Inflation ($\sigma_{me,\pi}$)	1.24	(0.14)	1.17	(0.16)	0.93	(0.49)	1.28	(0.34)
Standard Deviation: Interest Rate ($\sigma_{me,r}$)	0.09	(0.07)	0.12	(0.09)	1.52	(0.15)	0.13	(0.05)
Value of Objective Function	60.0		92.3		1431.3		61.0	
Minimum χ^2 statistic	34.7		34.1		>100		>100	
p-value DD test	0.05		0.04		<0.01		-	

Note: The table presents estimates of the pure models where firms use only one pricing mechanism and of the weighted model where aggregate dynamics is the sum of non-interacting economies with a single type of price setting. In the weighted model, s_3 is set to zero since inflation does not respond to shocks when only ROT firms are present. We use contemporaneous covariances and cross-autocovariances up to three lags. The truncation of past expectations for sticky-information firms is p=12. Data are from 1984:Q1 to 2008:Q2. Standard errors are constructed using non-parametric bootstrap. Bootstraps are done by running a 4-lag VAR on our data, and using the VAR coefficients and residuals to generate 2000 replications of the data which are used to re-estimate the model in each bootstrap replication. Minimum χ^2 statistic is computed as in Newey (1985). *P-value DD test* is the simulated probability value for the distance difference test (based on the difference in minimum χ^2 statistics) of imposed restrictions. See text and appendix for details on estimation approach.

Table 3: Variance Decomposition

Model	Policy	Preference	Technology
	Source of Variance of Growth in Output		
Model	Policy	Preference	Technology
Hybrid	5	85	10
Sticky-Price	5	72	23
Sticky-Info	20	80	0
Flexible	0	67	33
	Source of Variance of Inflation		
Model	Policy	Preference	Technology
Hybrid	5	25	70
Sticky-Price	5	41	54
Sticky-Info	50	44	7
Flexible	57	29	14
	Source of Variance of Interest Rates		
Model	Policy	Preference	Technology
Hybrid	10	90	0
Sticky-Price	5	95	0
Sticky-Info	25	75	0
Flexible	0	67	33

Note: Table presents variance decompositions from structural shocks given the parameter estimates for the hybrid model from Table 1 and the pure models from Table 2. Horizon is four quarters.

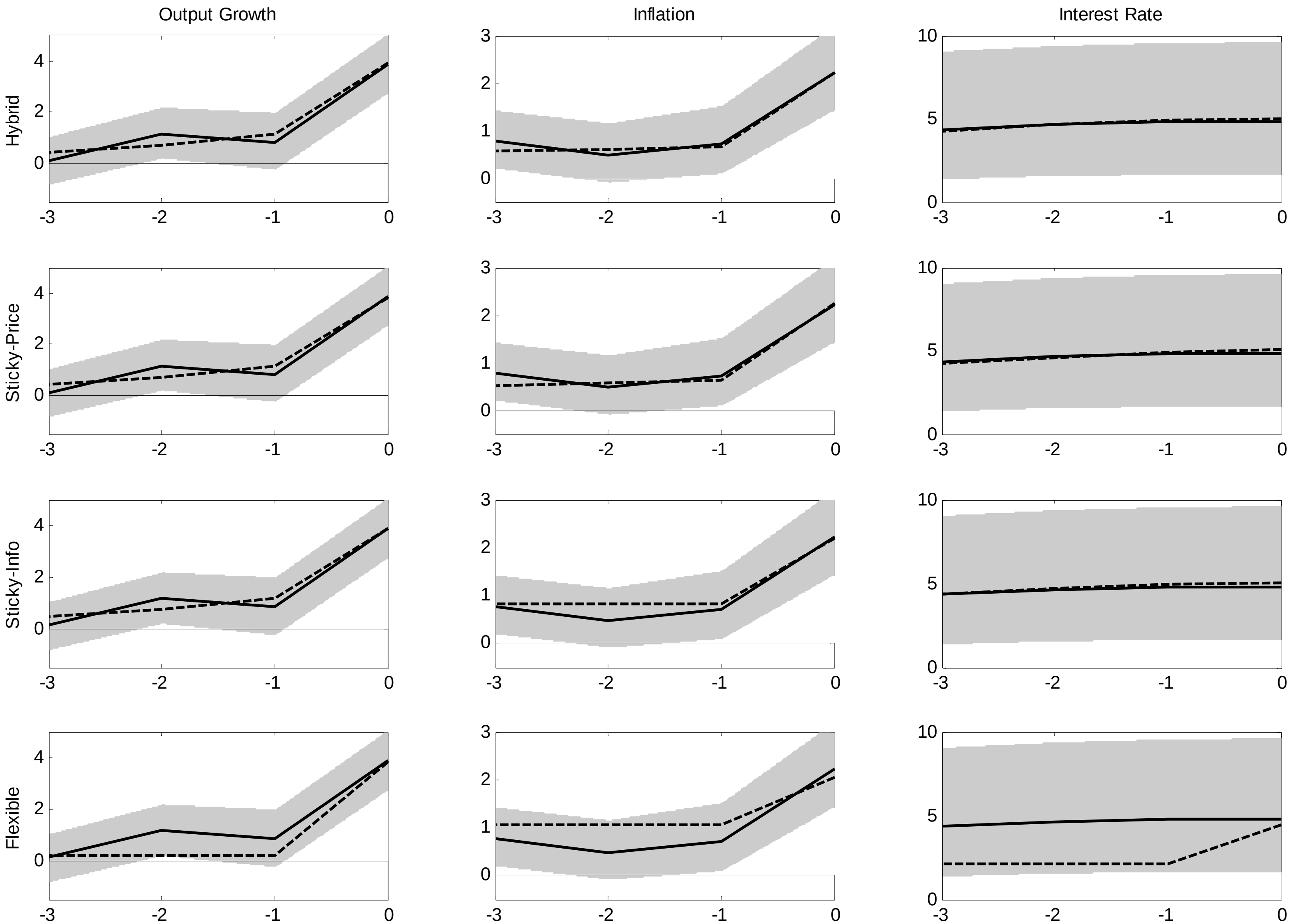
Table 4: Robustness of Estimates

	More moments		Diagonal Weighting Matrix		Indivisible Labor		Response to Output Gap		AR(1) Interest Smoothing		Truncation $p = 24$	
	estimate	(s.e.)	estimate	(s.e.)	estimate	(s.e.)	estimate	(s.e.)	estimate	(s.e.)	estimate	(s.e.)
Fundamentals												
η	1		1		∞		1		1		1	
θ	10		10		10		10		10		10	
h	0.87	(0.09)	0.75	(0.18)	0.81	(0.06)	0.81	(0.12)	0.81	(0.19)	0.82	(0.10)
Taylor Rule												
ϕ_π	2.58	(0.93)	3.04	(0.80)	2.13	(0.52)	2.67	(0.73)	3.48	(0.98)	2.72	(0.71)
ϕ_{gy}	1.87	(0.87)	2.75	(1.09)	2.83	(0.86)	2.73	(0.90)	4.05	(1.18)	2.32	(1.00)
ϕ_x	0.00		0.00		0.00		0.02	(0.01)	0.00			
ρ_1	1.74	(0.09)	0.66	(0.16)	1.50	(0.20)	1.60	(0.17)	0.91	(0.11)	1.61	(0.19)
ρ_2	-0.79	(0.08)	0.14	(0.09)	-0.57	(0.17)	-0.66	(0.15)	0.00		-0.67	(0.13)
Price-Setting												
s_1	0.57	(0.17)	0.48	(0.18)	0.49	(0.14)	0.61	(0.15)	0.60	(0.14)	0.63	(0.12)
s_2	0.24	(0.12)	0.16	(0.10)	0.00	(0.00)	0.23	(0.10)	0.15	(0.07)	0.22	(0.09)
s_3	0.11	(0.07)	0.18	(0.12)	0.51	(0.14)	0.08	(0.05)	0.09	(0.05)	0.08	(0.06)
δ_{sp}	0.82	(0.11)	0.76	(0.15)	0.85	(0.02)	0.80	(0.12)	0.81	(0.09)	0.81	(0.10)
δ_{si}	0.95	(0.15)	0.65	(0.24)	0.52	(0.16)	0.95	(0.15)	0.94	(0.16)	0.95	(0.09)
Shocks												
ρ_q	0.79	(0.15)	0.85	(0.11)	0.85	(0.23)	0.84	(0.15)	0.89	(0.08)	0.83	(0.10)
σ_r	0.02	(0.01)	0.89	(0.49)	0.39	(0.13)	0.15	(0.08)	0.47	(0.22)	0.13	(0.13)
σ_q	11.70	(4.31)	10.61	(3.75)	8.66	(3.25)	9.52	(3.99)	10.63	(3.35)	9.37	(3.36)
σ_a	3.46	(1.54)	1.56	(0.95)	0.85	(0.39)	3.32	(1.32)	2.49	(1.00)	3.39	(1.37)
Measurement Error												
$\sigma_{me,gy}$	1.28	(0.48)	1.30	(0.47)	1.42	(0.53)	1.45	(0.37)	1.50	(0.32)	1.47	(0.49)
$\sigma_{me,\pi}$	1.33	(0.19)	1.19	(0.20)	1.20	(0.44)	1.24	(0.15)	1.20	(0.18)	1.25	(0.32)
$\sigma_{me,r}$	0.20	(0.13)	0.51	(0.29)	0.10	(0.04)	0.12	(0.08)	0.10	(0.06)	0.12	(0.06)
Value of Obj. Function	123.4		4.3		73.1		50.9		56.8		51.6	
Minimum χ^2 statistic	221.8		24.0		31.2		21.7		27.5		20.1	
p-value DD test	-		-		-		0.37		0.02		-	

Note: The table presents robustness estimates of the baseline model. The truncation of past expectations for sticky-information firms is p=12. We use contemporaneous covariances and cross-autocovariances up to three lags unless otherwise specified. Data are from 1984:Q1 to 2008:Q2. In the scenario "More moments", we use contemporaneous covariances and cross-autocovariances up to eight lags.

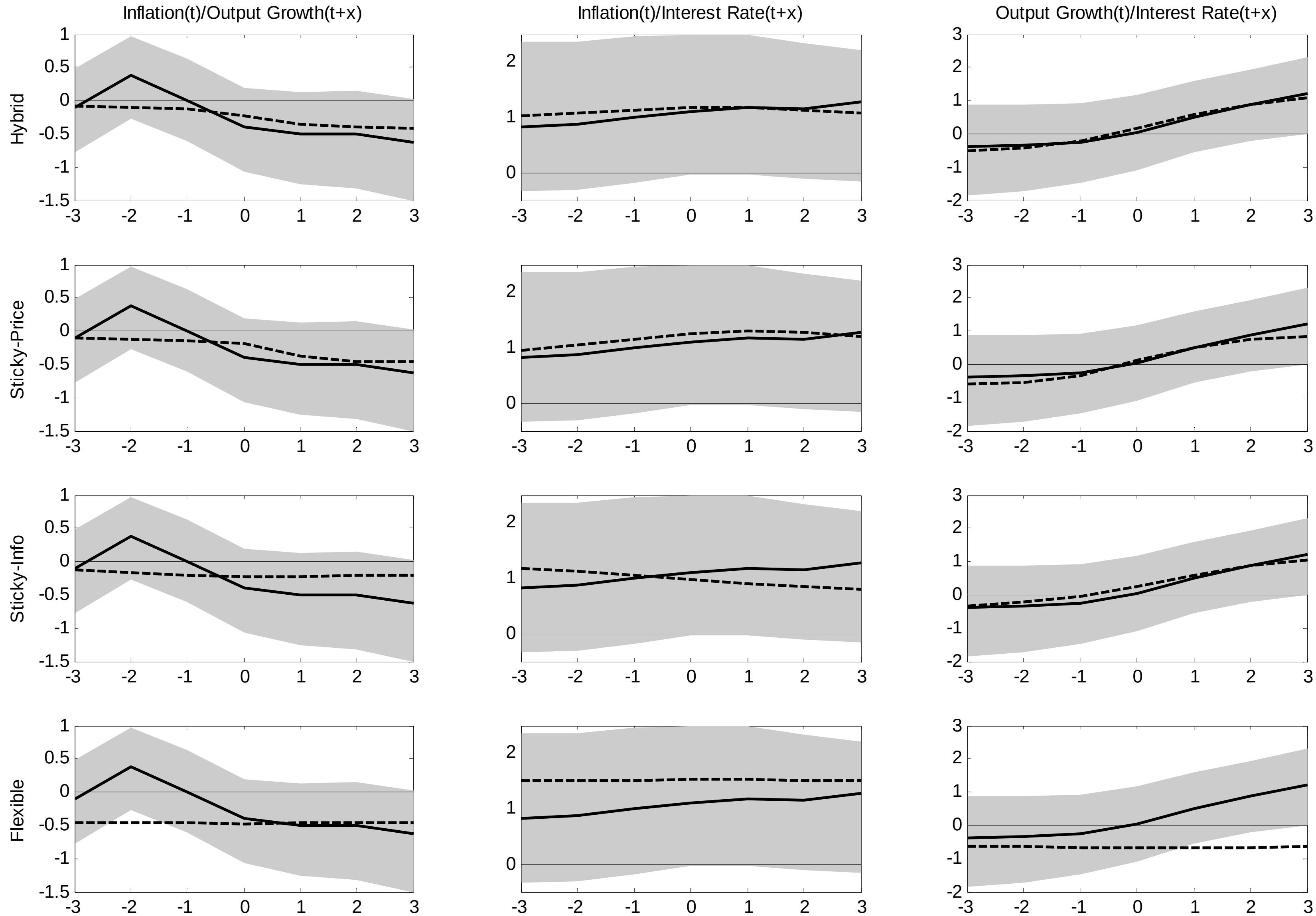
Standard errors are constructed using non-parametric bootstrap. Bootstraps are done by running a 4-lag VAR on our data, and using the VAR coefficients and residuals to generate 2000 replications of the data which are used to re-estimate the model in each bootstrap replication. Minimum χ^2 statistic is computed as in Newey (1985). *P-value DD test* is the probability value for the distance difference test (based on the difference in minimum χ^2 statistics) of imposed restrictions. See text and appendix for details on estimation approach.

Figure 1: Autocovariances of Observable Variables



Note: The figure plots autocovariances of the observable variables in the data (1984:Q1-2008:Q2), as the black bold lines, as well as those predicted by the hybrid model and pure models (using estimates in Tables 1 and 2), as the bold black dashed lines. The grey shaded areas are bootstrapped 95% confidence intervals. Bootstraps are done by running a 4-lag VAR on our data, and using the VAR coefficients and residuals to generate 2000 replications of the data, from which we generate a distribution of autocovariances. The horizontal axis indicates the timing in quarters of the lagged variable used in the autocovariance.

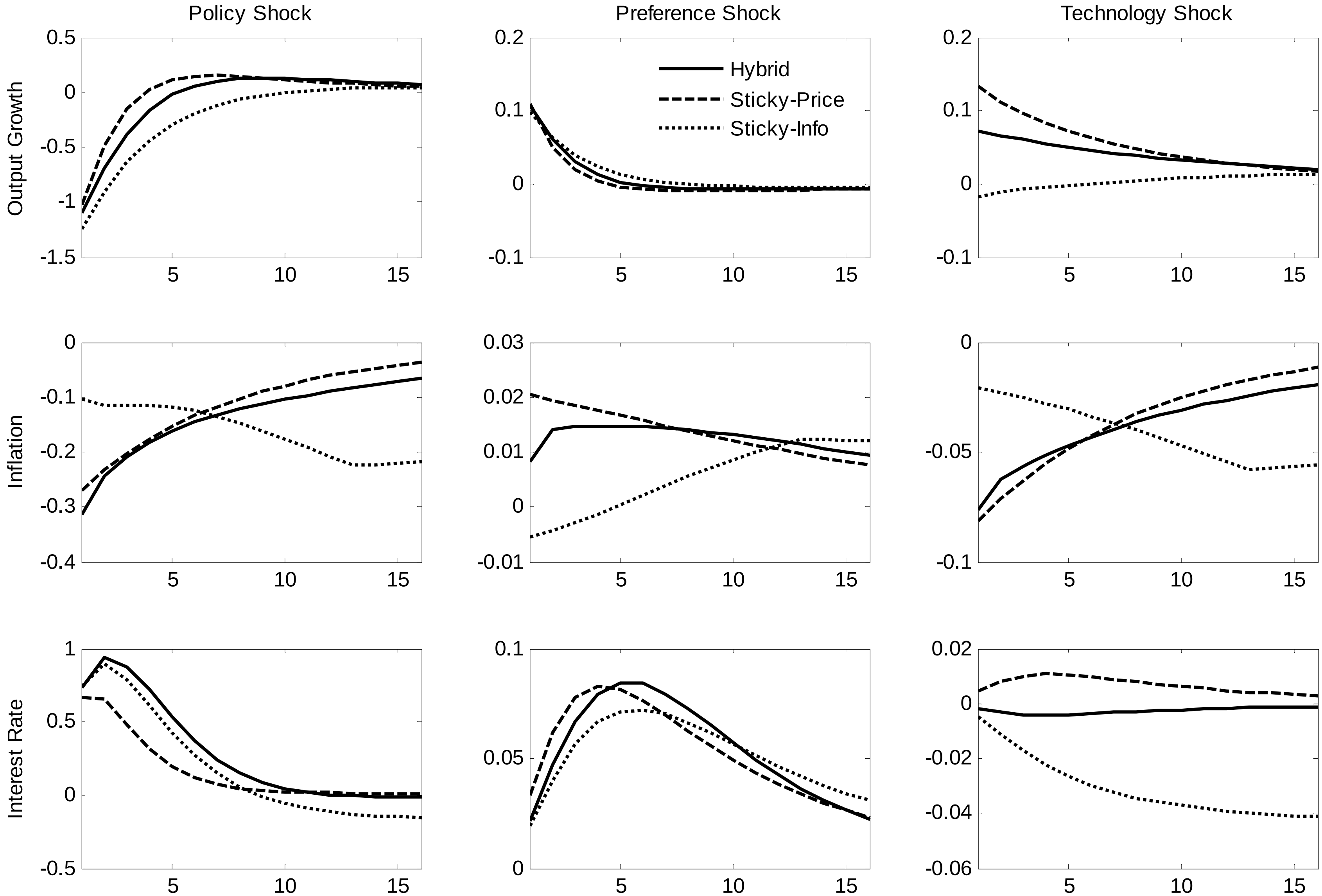
Figure 2: Cross-Covariances of Observable Variables



Note: The figure plots cross-autocovariances of the observable variables: output growth (*gy*), inflation (π), and interest rates (r) in the data (1984:Q1-2008:Q2) and those predicted by the hybrid model as well as those predicted by the pure models (using estimates in Table

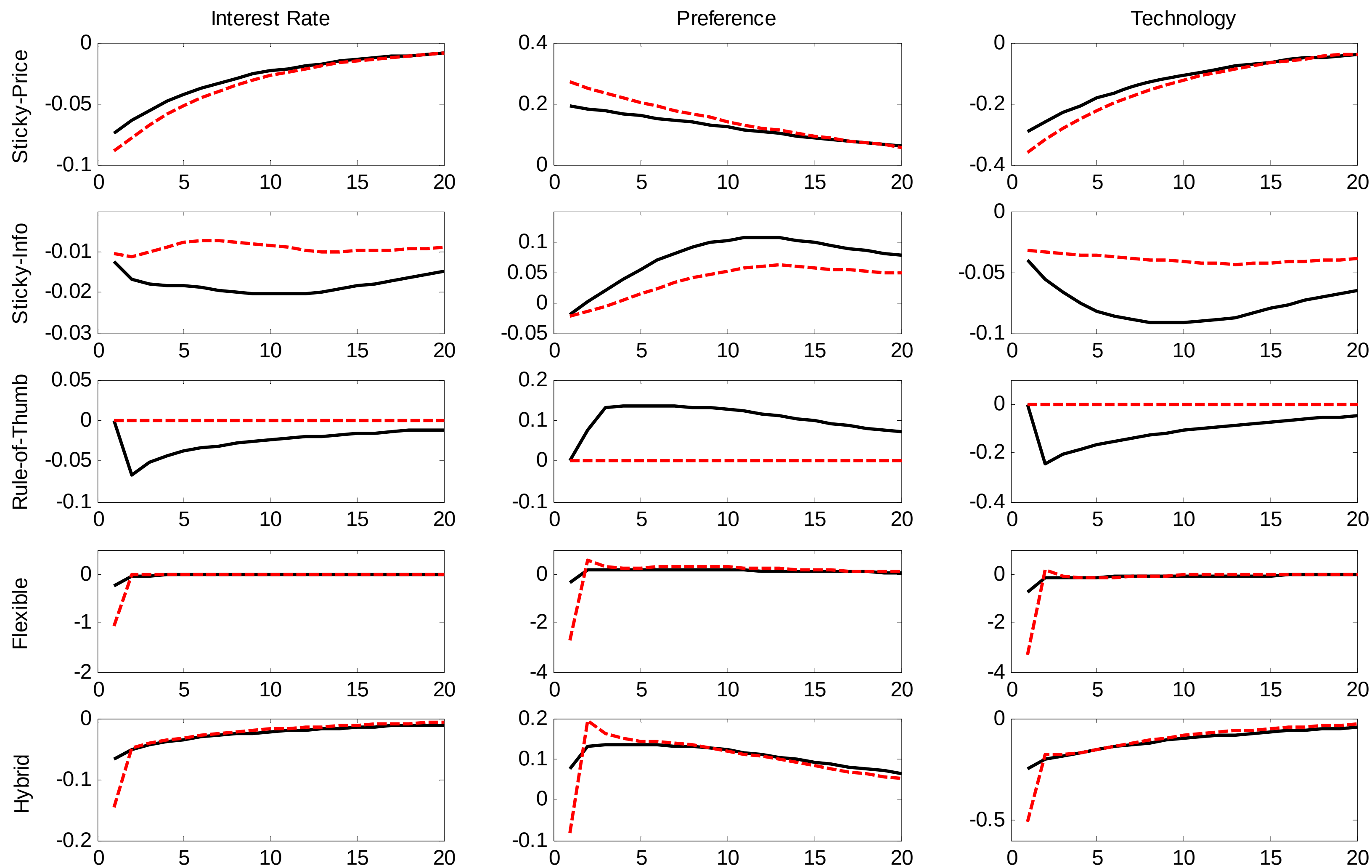
1). Black solid lines are from data while the bold dashed black lines are those of each model. The grey shaded areas are bootstrapped 95% confidence intervals. Bootstraps are done by running a 4-lag VAR on our data, and using the VAR coefficients and residuals to generate 2000 replications of the data, from which we generate a distribution of cross-autocovariances. The horizontal axis indicates the timing of the variable used in the cross-autocovariances (negative numbers indicate lags, positive numbers are leads).

Figure 3: Impulse response functions



Note: The figure plots impulse responses (percent deviation from steady-state) of baseline (hybrid), pure sticky-price and pure sticky-information models (based on estimates reported in Tables 1 and 2) to a unit innovation to monetary policy, preference shock, and technology. Time is in quarters on the horizontal axis.

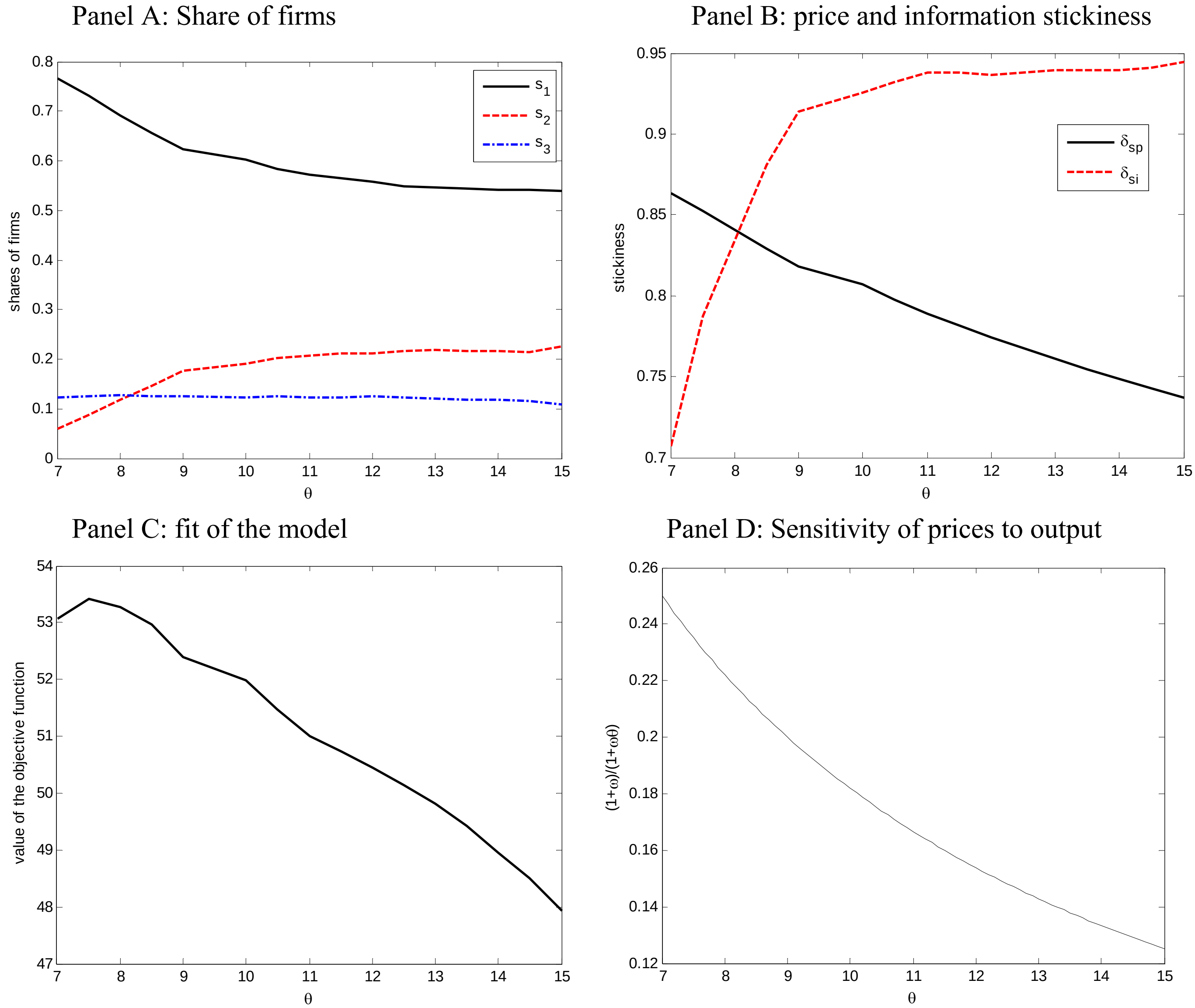
Figure 4: Sector-Specific vs. Pure Model Inflation



Note: The figure displays the response of inflation (percent deviation from steady-state) to one standard deviation shocks (labeled on top). Black solid lines indicate the response of inflation in each sector (labeled at left) within the hybrid model (using estimates of Table 1) while the red dash lines indicate the response of a pure model consisting only of that sector's type of firms (i.e., $s_d = 1$ for sector d).

The bottom row compares the response of aggregate inflation in the hybrid model (in black solid lines) to a weighted sum of inflation rates from the pure models (red dashed lines), where the weights are the effective weights (s^{CPI}) of each sector from the baseline estimates. Baseline parameter estimates are used in each case. Time is in quarters on the horizontal axis.

Figure 5: Robustness of Estimates to Elasticity of Substitution (θ)

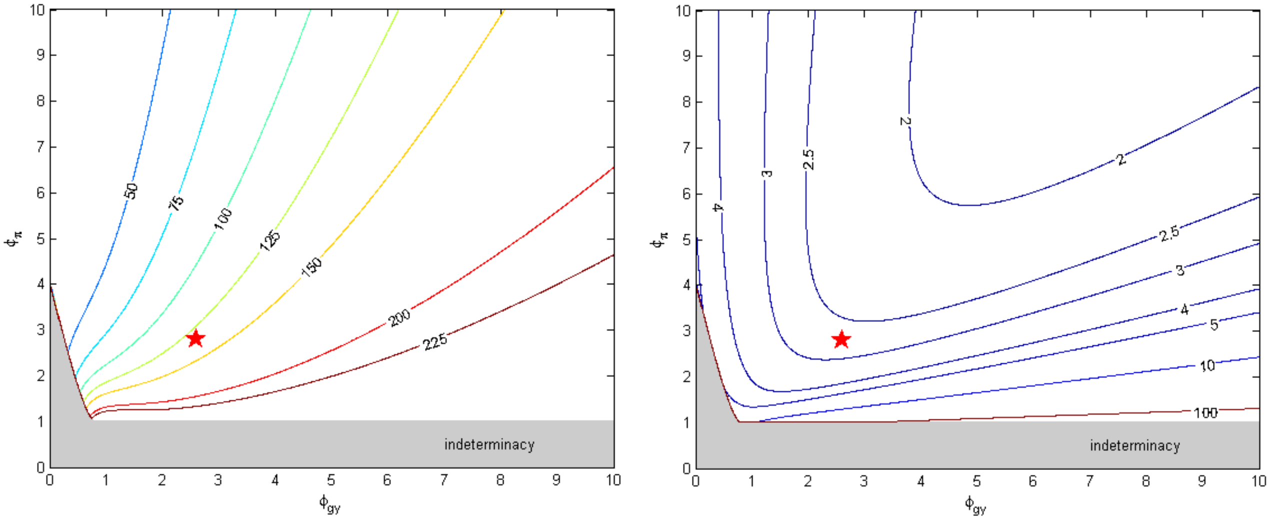


Note: The panels display estimation results of the baseline model for different values of θ, as indicated on the horizontal axis of each panel. For each value of θ, we ran a chain of 500,000 iterations, dropping the first 100,000 iterations. Panel A presents the estimated shares of sticky price (s_1), sticky-information (s_2), and rule-of-thumb firms (s_3) for different values of θ. Panel B presents the estimated levels of price rigidity (δ_{sp}) and informational rigidity (δ_{si}) for different values of θ. Panel C presents values of the objective function (averaged across chains) for each value of θ. Panel D plots the sensitivity of prices to change in output. A lower value on the vertical axis corresponds to a higher degree of strategic complementarity.

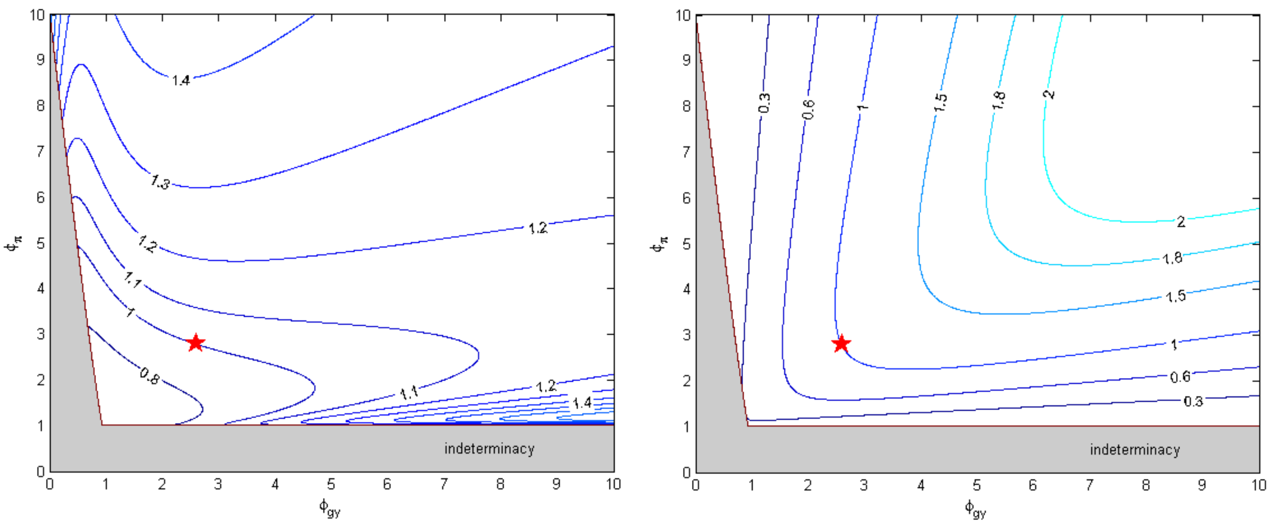
Figure 6. Welfare isoloss maps.

Loss function L_1 *Loss function L_2*

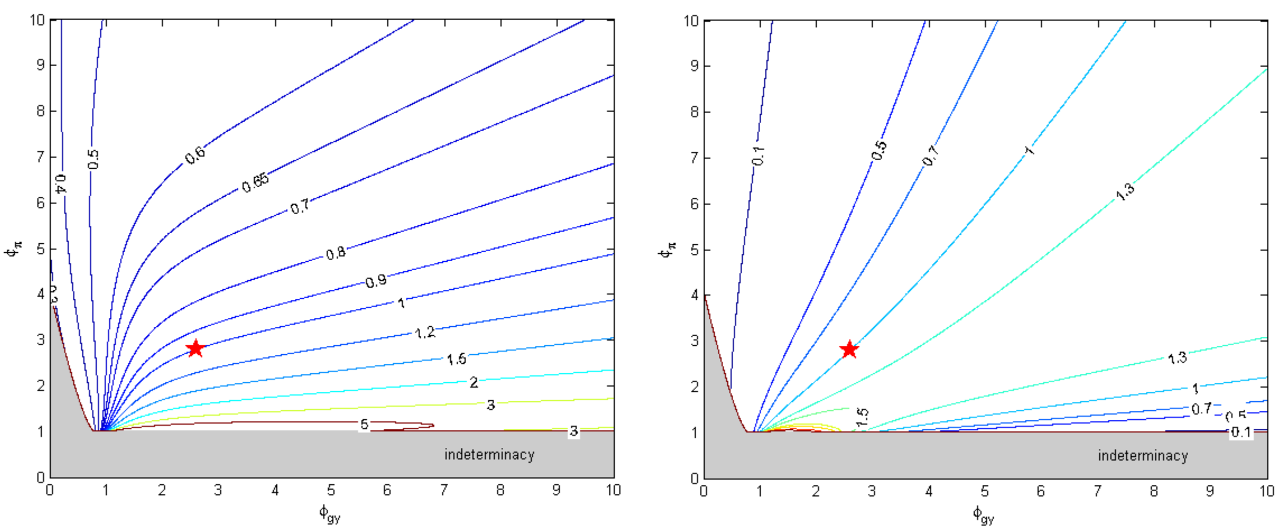
Panel A: Baseline hybrid model.



Panel B: Ratio of the relative map for pure sticky-price model to the relative map for the hybrid model.



Panel C: Ratio of the relative map for pure sticky-information model to the relative map for the hybrid model.



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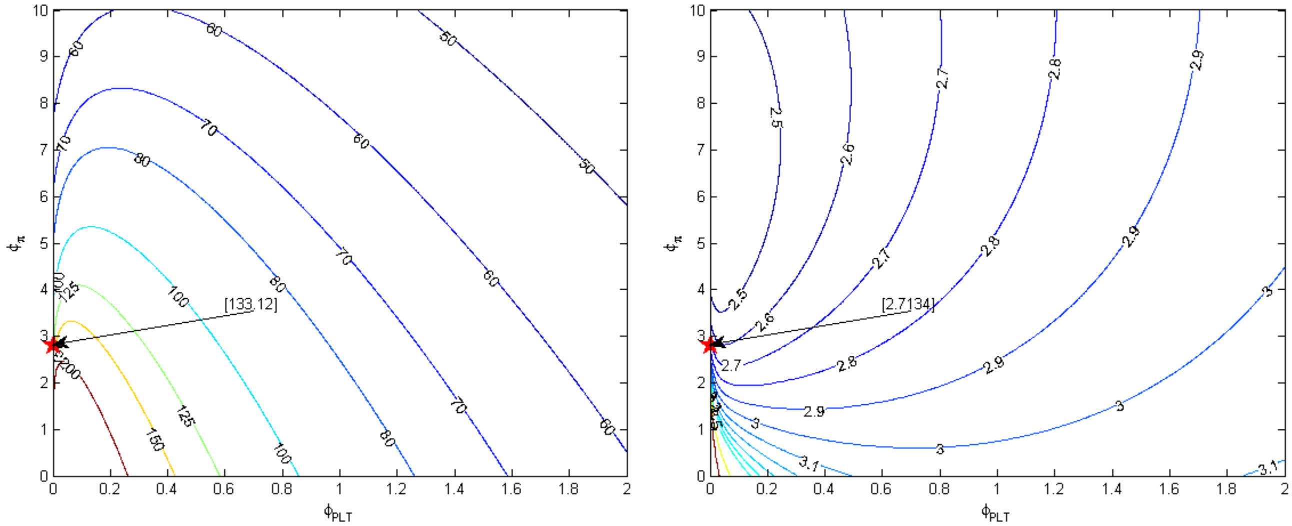
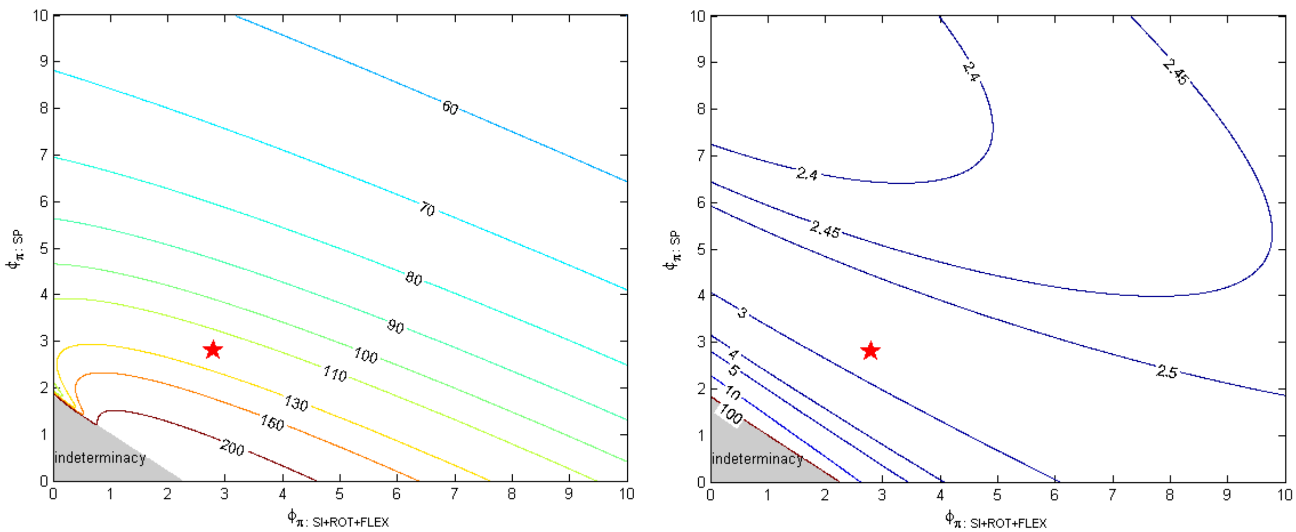
Panel D. Price level targeting.



Panel E. Differential responses to sector-specific inflation.



Notes: The figure plots isoloss maps for two welfare functions L_1 and L_2 for various combinations of the policy reaction function (Taylor rule). Volatilities of the variables are computed using the parameter estimates of the hybrid model. The red star indicates the position of the estimated Taylor rule. In panels A, B and C, ϕ_{gy} on the horizontal axis shows the long-run response of the policy instrument (interest rate) to a unit increase in the output growth rate. On the vertical axis, ϕ_π shows the long-run response of the policy instrument (interest rate) to a unit increase in inflation. Other parameters in the Taylor rule (interest rate smoothing, volatility of the interest rate shock) are held constant. In panel D, the figures in square parentheses show the value of the social loss function evaluated at the estimated Taylor rule. On the horizontal axis, ϕ_{PLT} shows the long-run response of the policy instrument (interest rate) to a unit increase in the deviation of the price level from its target. On the vertical axis, ϕ_{π} shows the long-run response of the policy instrument (interest rate) to a unit increase in inflation. Other parameters in the Taylor rule (interest rate smoothing, volatility of the interest rate shock, output growth rate response) are held constant. In panel E, $\phi_{\pi:\mathrm{SP+ROT+FLEX}}$ on the horizontal axis shows the long-run response of the policy instrument (interest rate) to a unit increase in aggregate inflation in the sticky-information, rule-of-thumb and flexible price sectors. On the vertical axis, $\phi_{\pi:\mathrm{SP}}$ shows the long-run response of the policy instrument (interest rate) to a unit increase in inflation in the sticky-price sector. Other parameters in the Taylor rule (interest rate smoothing, volatility of the interest rate shock, output growth rate response) are held constant. The shaded region shows the Taylor rule parameter combinations associated with equilibrium indeterminacy.

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[1] Models in Sims (2003), Woodford (2001), and Mankiw and Reis (2002) are prime examples.

[2] Empirical work typically finds a large amount of heterogeneity in the frequency of price changes by firms, as well as in the source of costs to changing prices. For example, Bils and Klenow (2004) find that there are large differences in durations between price changes across sectors, while Zbaracki et al (2004) report significant information costs.

[3] Sticky-price firms are modeled a la Calvo (1983), sticky-information firms are as in Mankiw and Reis (2002), and rule-of-thumb firms always update prices by last period's inflation rate, as in Barsky and Kilian (2001).

[4] See Gali and Gertler (1999) and Rudd and Whelan (2006).

[5] See Woodford (2003) for optimal monetary policy based on sticky-prices and Ball et al (2005) for the sticky-information model.

[6] Technically this implies that the relative price level of rule-of-thumb firms is indeterminate in a stationary steady-state. This can be avoided by assuming a Poisson probability 1-δ_{rot} that each firm is allowed to set its price equal to $P_t^{\#}$. Taking the limit as δ_{rot} goes to one leads to a well-defined relative price level equal to $P^{\#}/P$. We omit this in the text for simplicity but assume it implicitly later when we characterize the steady-state.

[7] We formally prove this result in Coibion and Gorodnichenko (2008b).

[8] For these sums to be well-defined in the steady-state requires that $\gamma_2 < 1$. Note that we express the reset price in terms of optimal prices rather than real marginal costs. The reason is that real marginal costs are also a

function of the price dispersion D_t. With non-zero trend inflation, this dispersion term has first order effects. By expressing price setting decisions in terms of desired optimal prices, we reduce the state space of the model by eliminating the need to keep track of the dynamics of price dispersion.

[9] For the relative reset price to be well-defined in equilibrium requires the additional condition that $\delta_{sp}\bar{\pi}^{1-\theta} < 1$.

[10] We follow Ireland (2004) and allow for the central bank to respond to output *growth* rather than some measure of the output gap. Our qualitative results are insensitive to the inclusion of an additional output gap term in the Taylor rule, as shown in section 4.4.

[11] In addition, the theoretically motivated output gap would tend to be poorly approximated by standard detrending methods (see Andres et al (2005)). Gorodnichenko and Ng (2009) also show that using growth rates of variables could lead to better statistical estimates than using levels of persistent variables.

[12] Sargent (1989), Watson (1993) and others emphasize the importance of measurement errors in reported macroeconomic variables as well as in improving the fit of dynamic stochastic general equilibrium models. We introduce measurement errors to absorb those short-term fluctuations in macroeconomic variables that are unrelated to structural shocks.

[13] These authors find that W equal to the identity matrix performs better than the optimal weighting matrix in the context of estimating covariance structures. The optimal weighting matrix, which contains high order moments, tends to correlate with the moments and this correlation undermines the performance of the method of moments estimator. We investigate the robustness of our results to the weighting matrix in section 4.4.

[14] One could of course study the same predicted moments as we do based on alternative estimation procedures. However, it is well-known that when one estimates a model using one set of moments, the resulting estimates may then fare poorly on an alternative set of moments (see e.g. Dupor, Han and Tsai (2009)). Thus, we use moments that have an intuitive economic interpretation in the estimation procedure to derive greater insight into why the estimated parameters come out the way they do. This task is harder to accomplish with alternative estimators such as MLE.

[15] We focus on this period rather than the full sample because of the structural break in the monetary policy reaction function as well as trend inflation which occurred in the early 1980s.

[16] We consider the effect of using more moments in the robustness section 4.4.

[17] The lower bound on pricing and information rigidities is imposed to avoid identification issues, since when these rigidities are low, firms in these sectors behave very much like flexible-price full-information firms, making identification of shares of firms tenuous. Likewise, we set an upper bound to avoid scenarios where firms reset prices very infrequently. In our estimation procedure we also restrict parameters to be consistent with a unique determinate rational expectation equilibrium. We calculated that, for the baseline specification, the MCMC chain generated less than 0.05% of draws which led to non-uniqueness/non-existence. Thus, most of our draws were away from the indeterminacy region. In addition, when we ran multiple long (2 million draws or more) chains, we observed that the averages across chains converged to very similar values as our baseline estimates, which is consistent with the chains exploring the parameter space sufficiently well. We also re-ran chains while fixing close-to-boundary parameters and we found very similar point estimates and standard errors for other parameters. Results are available upon request.

[18] The share of variance attributed to measurement error is 51%, 68%, and 0.2% for output growth rate, inflation rate, and interest rate respectively. Although the measurement errors soak up a relatively large fraction of contemporaneous variation in output growth and inflation, they have no effect on (auto)covariances which the model can match well. The main reason why we have to rely on measurement errors is because there is a clear break in the size of the autocovariances of output growth rate and inflation rate. These estimates are in line with previous studies. For example, Watson (1993) reports that the share of errors in the statistical model of the economy should be in the 40-60% range of total variation when one uses a basic real business cycle model. These estimates are also consistent with the amount of sampling uncertainty in macroeconomic series. For example, Broda and Weinstein (2007) report that the standard deviation of the sampling error alone in the CPI quarterly inflation rate is about 0.5. The standard deviation of the inflation rate in the sample analyzed in Broda and Weinstein is 0.68 so that the measurement error can easily account for 50% of variation in the inflation rate.

[19] The bootstrap is done by running a VAR(4) on our measures of GDP growth, inflation, and interest rates over the same time period as our sample. We then use the VAR to simulate new data of the same length and calculate the auto and cross-covariances from the simulated data. We use 2,000 bootstraps to generate 95% confidence intervals.

[20] We omit responses from the flexible price model because a) flexible price and rule-of-thumb firms account for a small fraction of firms in the hybrid model and b) the responses of flexible firms are very large on impact and dwarf those of the other models. The estimates for each model are taken from Table 2.

[21] With policy responding to endogenous variables, the behavior of firms in pure models should differ from the hybrid model even in the absence of pricing complementarities. To address this issue, we considered a version of the model with exogenous money supply and a money demand curve. The results were almost identical to those reported in the paper so we can argue that the dynamics in Figure 4 are driven largely by strategic complementarity in price setting rather than by the endogenous response of monetary policy-makers. However, we cannot eliminate the indirect interaction of firms via aggregate demand which is present in the hybrid model and absent in the weighted sum of pure models. Thus, by comparing the hybrid and weighted sum of pure models, we observe the joint effect of direct (pricing complementarities) and indirect (aggregate demand) interaction between firms. We are grateful to an anonymous referee for pointing these issues out.

[22] In other words, the economy is split into four islands, each of which is populated with a single-type of price setting firms, there is no direct interaction across islands via pricing complementarities, input and output markets as well as any macroeconomic variable, aggregate behavior is a (weighted) sum of dynamics across islands and then we compare these aggregate dynamics with the dynamics in the hybrid model when different types of firms are allowed to interact.

[23] Note that we dropped rule-of-thumb firms because this model yields a zero response of inflation to all shocks in the absence of other firms.

[24] In Monte Carlo simulations (available upon request), we found that estimates based on the identity weighting matrix have better statistical properties than estimates based on the diagonal weighting matrix and the optimal weighting matrix in time series of the same length as ours.

[25] Alternatively, one can interpret the ratio of the relative welfare maps as the difference-in-difference estimator for the changes in the welfare changes when the policymaker considers alternative values of ϕ_π and ϕ_{gy} in the Taylor rule.

[26] Note that moving along the 45° line in Panel E corresponds to moving along the vertical line that passes the estimated Taylor rule parameter combination in Panel A.