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High Frequency Identification of Monetary Non-Neutrality: The Information Effect

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A Construction of the Policy News Shock

The policy news shock is constructed as the first principle component of the change in five interest rates. The first of these is the change in market expectations of the federal funds rate over the remainder of the month in which the FOMC meeting occurs. To construct this variable we use data on the price of the federal funds futures contract for the month in question. The federal funds futures contract for a particular month (say April 2004) trades at price p and pays off $100 - \bar{r}$ where $\bar{r}$ is the average of the effective federal funds rate over the month.[1] To construct the change in expectations for the remainder of the month, we must adjust for the fact that a part of the month has already elapsed when the FOMC meeting occurs. Suppose the month in question has m_0 days and the FOMC meeting occurs on day d_0. Let $f^1_{t-\Delta t}$ denote the price of the current month's federal funds rate futures contract immediately before the FOMC announcement and f^1_t the price of this contract immediately following the FOMC announcement. Let r_{-1} denote the average federal funds rate during the month up until the point of the FOMC announcement and r_0 the average federal funds rate for the remainder of the month. Then

$$f^1_{t-\Delta t} = \frac{d_0}{m_0} r_{-1} + \frac{m_0 - d_0}{m_0} E_{t-\Delta t} r_0,$$

[1]Fed funds futures have been traded since 1988. The effective federal funds rate is the rate that is quoted by the Federal Reserve Bank of New York on every business day. See the Chicago Board of Trade Reference guide `http://www.jamesgoulding.com/Research_II/FedFundsFutures/FedFunds(FuturesReferenceGuide).pdf` for a detailed description of federal funds futures contracts. On a trading day in March (say), the April federal funds futures contract is labeled as 2nd expiration nearby and also as 1st beginning nearby, in reference to the month over which $\bar{r}$ is computed.

$$f_t^1 = \frac{d_0}{m_0} r_{-1} + \frac{m_0 - d_0}{m_0} E_t r_0.$$

As a result

$$E_t r_0 - E_{t-\Delta t} r_0 = \frac{m_0}{m_0 - d_0}(f_t^1 - f_{t-\Delta t}^1).$$

When the FOMC meeting occurs on a day when there are 7 days or less remaining in a month, we instead use the change in the price of next month's fed funds futures contract. This avoids multiplying $f_t^1 - f_{t-\Delta t}^1$ by a very large factor.

The second variable used in constructing the policy news shock is the change in the expected federal funds rate at the time of the next scheduled FOMC meeting. Similar issues arise in constructing this variable as with the variable described above. Let m_1 denote the number of days in the month in which the next scheduled FOMC meeting occurs and let d_1 denote the day of the meeting. The next scheduled FOMC meeting may occur in the next month or as late as 3 months after the current meeting. Let $f_{t-\Delta t}^n$ denote the price of the federal funds rate futures contract for the month of the next scheduled FOMC meeting immediately before the FOMC announcement and f_t^n the price of this contract immediately following the FOMC announcement. Let r_1 denote the federal funds rate after the next scheduled FOMC meeting. Analogous calculations to what we present above yield

$$E_t r_1 - E_{t-\Delta t} r_1 = \frac{m_1}{m_1 - d_1}\left[(f_t^n - f_{t-\Delta t}^n) - \frac{d_1}{m_1}(E_t r_0 - E_{t-\Delta t} r_0)\right].$$

As with the first variable, if the next scheduled FOMC meeting occurs on a day when there are 7 days or less remaining in a month, we instead use the change in the price of next month's federal funds futures contract.

The last three variables used are the change in the price of three eurodollar futures at the time of the FOMC announcements. A eurodollar futures contract expiring in a particular quarter (say 2nd quarter 2004) is an agreement to exchange, on the second London business day before the third Wednesday of the last month of the quarter (typically a Monday near the 15th of the month), the price of the contract p for 100 minus the then current three-month US dollar BBA LIBOR interest rate. The contract thus provides market-based expectations of the three month nominal interest rate on the expiration date.[2] We make use of eurodollar futures at horizons of n quarters in the future for n = 2, 3, 4 or, more precisely, the expiration date of the "n quarter" eurodollar future is between $n-1$ and n quarters in the future at any given point in time.

[2]Eurodollar futures began trading in the early 1980's. See the CME Group eurodollar futures reference guide `http://www.cmegroup.com/trading/interest-rates/files/eurodollar-futures-reference-guide.pdf` for more details about how eurodollar futures are defined.

We approximate the change in these variables over a 30-minute window around FOMC by taking the difference between the price in the last trade that occurred more than 10 minutes before the FOMC announcement and the first trade that occurred more than 20 minutes after the FOMC announcement. On control days in the analysis using the heteroskedasticity based estimation approach, we take the last trade before 2:05pm and the first trade after 2:35pm (since FOMC announcements tend to occur at 2:15pm). On some days (most often control days), trading is quite sparse and there sometimes is no trade before 2:05 or after 2:35. To limit the size of the windows we consider, we only consider trades on the trading day in question and until noon the next day. If we do not find eligible trades to construct the price change we are interested in within this window, we set the price change to zero (i.e., we interpret no trading as no price change).

B Rigobon's Heteroskedasticity-Based Estimator

Table 2 presents results from a heteroskedasticity-based estimator of the type developed by Rigobon (2003) and Rigobon and Sack (2004). The empirical model we consider in this analysis is the following. Let ϵ_t denote a pure monetary shock and suppose that movements in the policy indicator Δi_t we observe in the data is governed both by monetary and non-monetary shocks:

$$\Delta i_t = \alpha_i + \epsilon_t + \eta_t, \tag{1}$$

where η_t is a vector of all other shocks that affect Δi_t. Here α_i is a constant and we normalize the impact of ϵ_t and η_t on Δi_t to one. We wish to estimate the effects of the monetary shock ϵ_t on an outcome variable Δs_t. This variable is also affected by both the monetary and non-monetary shocks:

$$\Delta s_t = \alpha_s + \gamma \epsilon_t + \beta \eta_t. \tag{2}$$

The parameter of interest is γ, which should be interpreted as the impact of the pure monetary shock ϵ_t on Δs_t relative to its impact on Δi_t.

Our identifying assumption is that the variance of monetary shocks increases at the time of FOMC announcements, while the variance of other shocks is unchanged. Define $R1$ as a sample of narrow time intervals around FOMC announcements, and define $R2$ as a sample of equally narrow time intervals that do not contain FOMC announcements but are comparable on other dimensions (e.g., same time of day, same day of week, etc.). We refer to $R1$ as our "treatment" sample and $R2$

as our "control" sample. Our identifying assumption can then be written as

$$\sigma_{\epsilon,R1} > \sigma_{\epsilon,R2}, \text{ while } \sigma_{\eta,R1} = \sigma_{\eta,R2}.$$

Let Ω_{Ri} denote the variance-covariance matrix of $[\Delta i_t, \Delta s_t]$ in regime Ri. Then Ω_{Ri} is given by

$$\Omega_{Ri} = \begin{bmatrix} \sigma^2_{\epsilon,Ri} + \sum_j \sigma^2_{\eta,j} & \gamma\sigma^2_{\epsilon,Ri} + \sum_j \beta_{s,j}\sigma^2_{\eta,j} \\ \gamma\sigma^2_{\epsilon,Ri} + \sum_j \beta_{s,j}\sigma^2_{\eta,j} & \gamma^2\sigma^2_{\epsilon,Ri} + \sum_j \beta^2_{s,j}\sigma^2_{\eta,j} \end{bmatrix},$$

where j indexes the elements of η_t.

Notice that

$$\Delta\Omega = \Omega_{R1} - \Omega_{R2} = (\sigma^2_{\epsilon,R1} - \sigma^2_{\epsilon,R2}) \begin{bmatrix} 1 & \gamma \\ \gamma & \gamma^2 \end{bmatrix}.$$

Thus,

$$\gamma = \frac{\Delta\Omega_{12}}{\Delta\Omega_{11}} = \frac{\text{cov}_{R1}(\Delta i_t, \Delta s_t) - \text{cov}_{R2}(\Delta i_t, \Delta s_t)}{\text{var}_{R1}(\Delta i_t) - \text{var}_{R2}(\Delta i_t)}. \tag{3}$$

This is the estimator we use to construct the results in Table 2 and Table A.3. Notice that if we set the variance of the "background noise" η_t to zero, then the heteroskedasticity-based estimator, equation (3) reduces to the coefficient from an OLS regression of Δs_t on Δi_t. Intuitively, the full heteroskedasticity-based estimator can be thought of as the simple OLS estimator, adjusted for the "normal" covariance between Δs_t and Δi_t and the "normal" variance of Δi_t.

C Weak Instruments Robust Confidence Intervals

The confidence intervals in Table 2 are constructed using a more sophisticated bootstrap procedure than is conventional. The reason is that the conventional bootstrap approach to constructing confidence intervals yields inaccurate results in the case when there is a significant probability that the difference in the variance of Δi_t between the treatment and control sample is close to zero.[3] Figure C.1 illustrates that this is the case for the 1-day window estimation but not the 30-minute window. The problem is essentially one of weak instruments. Rigobon and Sack (2004) show that the estimator in equation (3) can be formulated as an IV regression. When the difference in the variance of Δi_t between the treatment and control sample is small, the instrument in this formulation is weak,

[3]Recall that the Rigobon estimator—equation (3)—is a ratio with the difference in the variance of Δi_t between the treatment sample and the control sample in the denominator. If the distribution of this difference has significant mass in the vicinity of zero, the sampling distribution of the estimator will have significant mass at large positive and negative values.

leading to biased point estimates and confidence intervals.

In Table 2, we, therefore, employ a weak-instruments robust approach to constructing confidence intervals. The approach we employ is a test inversion approach. A 95% confidence interval for our parameter of interest γ can be constructed by performing a hypothesis test for all possible hypothetical true values of γ and including those values that are not rejected by the test in the confidence interval.

The test statistic we use is

$$g(\gamma) = \Delta\text{cov}(\Delta i_t, \Delta s_t) - \gamma\Delta\text{var}(\Delta i_t), \tag{4}$$

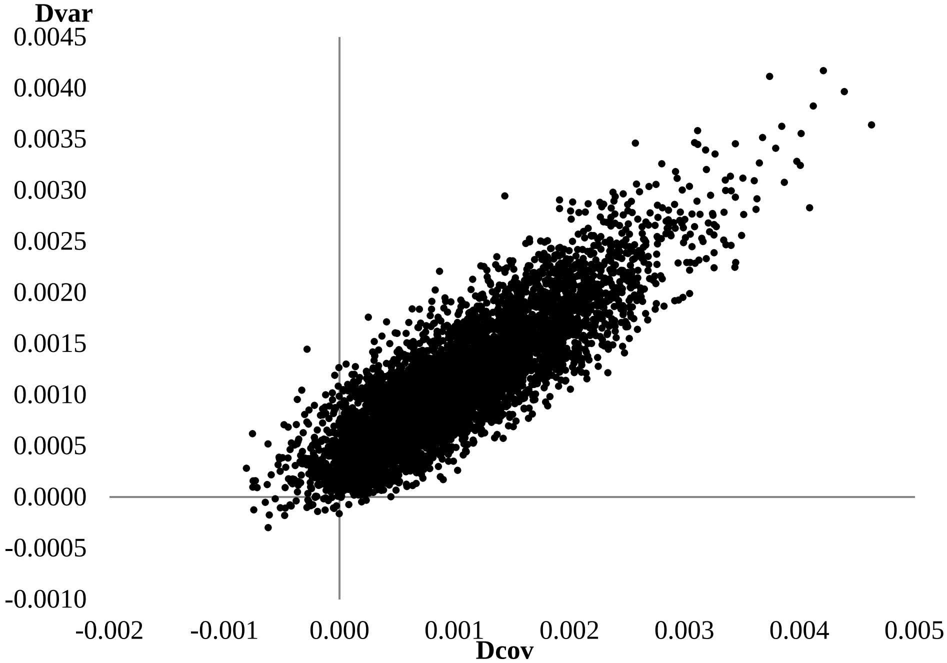
where Δcov and Δvar denote the difference between the covariance and variance, respectively, in the treatment and control samples.

Intuitively, $g(\gamma) = 0$ at the true value of γ. We estimate the distribution of $g(\gamma)$ for each hypothetical value of γ and include in our confidence interval values of γ for which $g(\gamma) = 0$ cannot be rejected. Figure C.2 plots the 2.5%, 50% and 97.5% quantiles of the distribution of $g(\gamma)$ as a function of γ for the 2-year nominal forward in the one-day window case. Values of γ for which the 2.5% quantile lies below zero and and 97.5% quantile lies above zero are included in the 95% confidence interval. This method for constructing confidence intervals is referred to as the Fieller method by Staiger, Stock, and Watson (1997) as it is an extension of an approach proposed by Fieller (1954). We use a bootstrap to estimate the joint distribution of Δcov and Δvar. Our approach is therefore similar to the grid bootstrap proposed by Hansen (1999) for a different application.

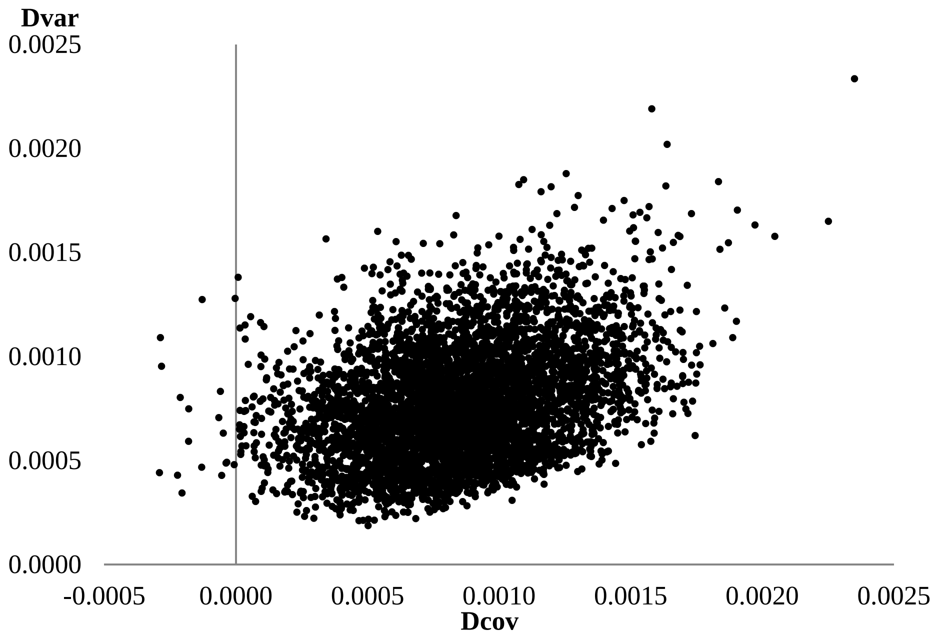
This more sophisticated procedure for constructing confidence intervals is not important for our baseline estimator based on changes in the policy news shock over a 30-minute window. In this case, the weak-IV robust confidence intervals coincide closely with the standard non-parametric bootstrap confidence interval reported in Table A.3. However, this weak-IV robust procedure is very important for the Rigobon estimator when the policy news shock is measured over a 1-day window.

D Risk Premia or Expected Future Short Rates

We present three sets of results that indicate that risk premium effects are not driving our empirical results: 1) the impact of our policy news shock on direct measures of expectations from the *Blue Chip Economic Indicators*; 2) the impact of our policy news shock on risk-neutral expected short rates



Panel A: 1-Day Window



Panel B: 30-Minute Window

Figure C.1: Scatter of Joint Distribution of Dcov and Dvar for 2-Year Nominal Forward Rate

Notes: Each point in the figure is a draw from our bootstrap. Dvar denotes the difference in variance of our policy news shock between the treatment and control sample. Dcov denotes the difference in the covariance of our policy news shocks and the 2-year nominal forward rate between the treatment and the control sample.

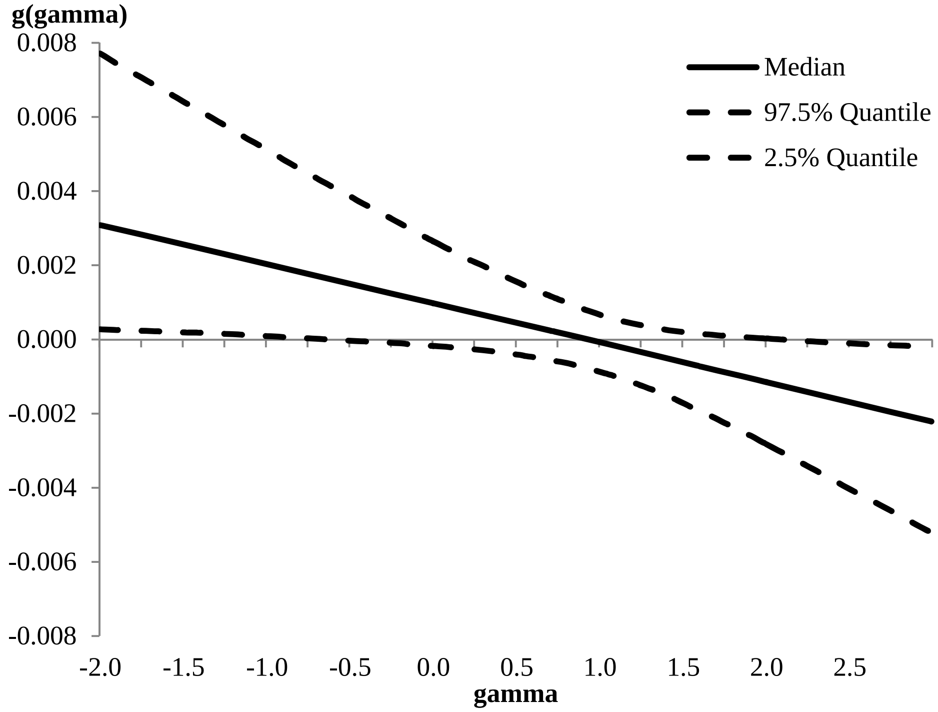


Figure C.2: Quantiles of the Distribution of $g(\gamma)$

Notes: Quantiles of the distribution of $g(\gamma)$ for different values of γ when estimating effect on the 2-year nominal forward rate using a 1-day window

from a state-of-the-art affine term structure model; and 3) the impact of our policy news shock on interest rates over longer event windows than in our baseline results.

Let us begin with our analysis of the Blue Chip forecast data. Blue Chip surveys professional forecasters on their beliefs about macroeconomic variables over the next two years in the first few days of every month. From this survey, it is possible to obtain direct measures of expectations that are not contaminated by risk premium effects. We use expectations about future values of the 3-month T-Bill rate as our measure of short-term nominal interest rate expectations and expectations about changes in the GDP deflator as our measure of expectations about inflation (and the difference between the two as our measure of expectations about short-term real rates).

We estimate the impact of monetary shocks on expectations by running regressions of the change from one month to the next in expectations regarding a particular forecast horizon on the policy news shock that occurs over the month except for those that occur in the first week of the month (because we do not know whether these occurred before or after the survey response). Unfortunately, Blue Chip asks respondents only about the current and subsequent calendar year on a monthly basis. So, fewer observations are available for longer-term expectations, leading to larger

Table D.1: Effects of Monetary Shocks on Survey Expectations

	Nominal	Real	Inflation
1 quarter	1.05	1.17	-0.12
	(0.73)	(0.78)	(0.24)
2 quarters	1.18	1.63	-0.44
	(0.75)	(0.78)	(0.31)
3 quarters	0.99	1.29	-0.30
	(0.72)	(0.77)	(0.24)
4 quarters	0.86	1.17	-0.32
	(0.71)	(0.69)	(0.23)
5 quarters	0.73	0.59	0.14
	(0.89)	(0.94)	(0.21)
6 quarters	1.84	1.60	0.23
	(0.89)	(0.88)	(0.24)
7 quarters	4.45	4.29	0.17
	(1.91)	(1.99)	(0.27)

Each estimate comes from a separate OLS regression. We regress changes in survey expectations from the *Blue Chip Economic Indicators* on the policy news shock. Since the Blue Chip survey expectations are available at a monthly frequency, we construct a corresponding monthly measure of our policy news shock. In particular, we use any policy news shock that occurs over the month except for those that occur in the first week (because we do not know whether these occurred before or after the survey response). The dependent variable is the change in the forecasted value of the variable listed at the top N quarters ahead, between this month's survey and last month's survey. See Appendix F for details. We consider the effects on expected future 3-month T-Bill rates, short-term real interest rates and inflation, where the inflation rate is the GDP deflator and the short-term real interest rate is calculated as the difference between the expected 3-month T-bill rate and the expected GDP deflator for a given quarter. The sample period is all regularly scheduled meetings between January 1995 and April 2014, except that we exclude the period from July 2008 through June 2009 and the aforementioned first-week meetings. The policy news shock is constructed on this sample period. The sample size is 120 for the first four rows of the table. It then falls to 75, 45, and 13 for rows 5 through 7, respectively. Robust standard errors are in parentheses.

standard errors.[4] The sample period for this analysis is January 1995 to April 2014, except that we exclude the apex of the 2008-2009 financial crisis as we do in our baseline analysis.

Table D.1 presents the results from this analysis. The table shows that the policy news shock has a persistent impact on expected short-term interest rates, both nominal and real. The interest rate effects are somewhat larger than in our baseline results, but rather noisily estimated. The effect on expected inflation is small and statistically insignificant at all horizons. The much larger standard errors in Table D.1 arise from the fact that the Blue Chip variables are available only at a monthly frequency as opposed to a daily frequency. Overall, these estimates appear consistent with our

[4]For example, towards the end of each year, forecasters are only asked about their beliefs a little more than 1-year in advance; while in the first quarter they are asked about their beliefs for almost the next full 2-years. Blue Chip also asks for longer-term inflation forecasts, but only twice a year (March and October) implying that there are too few observations to obtain meaningful estimates.

baseline findings that monetary shocks have large effects on expected short-term nominal and real rates.

Our second approach is to regress estimates of changes in expected future short rates from a state-of-the-art affine term structure model on our monetary policy shocks. Abrahams et al. (2015) employ an affine term structure model to decompose changes in both nominal and real interest rates at different maturities into changes in risk-neutral expected future short rates and changes in risk premia.[5] Table D.2 presents results based on their decomposition. The response of model-implied risk-neutral interest rates to our policy news shock is very similar to the response of raw interest rates in our baseline results. This piece of evidence, thus, points to our monetary shocks having large effects on future short-term nominal and real rates and small effects on expected inflation (even smaller than in our baseline results).

It is important to stress that the Abrahams et al. (2015) model by no means rules out the potential importance of risk premium effects. In fact, risk premia for long-term bonds are large and volatile in this model. While this model predicts that a large fraction of interest rate variation at other times *are* associated with risk premia, this is not the case for interest rate movements at the time of FOMC announcements. In this regard, our measure of the monetary shock appears to differ importantly from that of Hanson and Stein (2015). Our monetary shocks have virtually no effect on risk premia, as we describe above. In contrast, Hanson and Stein's measure (based on the 2-day change in the 2-year nominal yield around FOMC announcements, as we describe in section 3.2) is associated with large changes in risk premia (Abrahams et al., 2015). This suggests that Hanson and Stein's measure of monetary policy shocks is—either due to greater background noise, or because it picks up variation in interest rates further out in the yield curve—much more associated with movements in risk premia at the time of FOMC meetings than our policy news shock.

Our third approach to gauging the role of risk premia in our results is to consider longer event windows for the outcome variables of interest. Some models of liquidity premia (such as the one developed in Hanson and Stein (2015)) predict that we should see real interest rate effects dissipate quickly after the announcement.[6] Table D.3 presents the effects of our policy news shock on nominal and real interest rates over event windows of 1, 5, 10, 20, 60, 125, and 250 trading days.[7] While the

[5]What we refer to as the risk premia here is the difference between raw interest rate changes and changes in model-implied risk neutral interest rates. Abrahams et al. (2015) further decompose this difference into a term premium, a liquidity premium, and a model error term.

[6]Hanson and Stein (2015) present a behavioral model in which "search for yield" generates significant risk premium effects of monetary shocks that dissipate over time.

[7]In all cases, the policy news shock is measured over a 30-minute event window. We only vary the length of the event window for the dependent variables.

Table D.2: Response of Expected Future Short Rates and Risk Premia

	Expected Future Short Rates		Risk Premia	
	Nominal	Real	Nominal	Real
2Y Treasury Yield	1.01	0.86	0.09	0.20
	(0.27)	(0.17)	(0.10)	(0.18)
3Y Treasury Yield	0.93	0.82	0.13	0.21
	(0.26)	(0.18)	(0.15)	(0.19)
5Y Treasury Yield	0.76	0.60	-0.04	0.04
	(0.16)	(0.12)	(0.11)	(0.14)
10Y Treasury Yield	0.50	0.40	-0.12	0.04
	(0.11)	(0.08)	(0.14)	(0.14)
2Y Treasury Forward Rate	0.79	0.73	0.35	0.26
	(0.24)	(0.22)	(0.26)	(0.21)
3Y Treasury Forward Rate	0.61	0.56	0.21	0.32
	(0.19)	(0.17)	(0.29)	(0.25)
5Y Treasury Forward Rate	0.36	0.33	-0.11	0.14
	(0.08)	(0.08)	(0.17)	(0.17)
10Y Treasury Forward Rat	0.10	0.09	-0.18	0.04
	(0.02)	(0.02)	(0.18)	(0.12)

Each estimate comes from a separate OLS regression. The dependent variables in the first two columns are one-day changes in risk neutral yields and forwards from Abrahams et al. (2015) -- i.e., measures of expected future short rates. The dependent variables in the later two columns are the difference between one-day changes in raw yields and forwards and one-day changes in the risk neutral yields and forwards from Abrahams et al. (2015). We refer to this difference as the risk premia. It corresponds to the term premium, liquidity premium and model error in Abrahams et al. (2015). The independent variable is a change in the policy new shock over a 30 minute window around the time of FOMC announcements. The forward rates are one-year forwards at different horizons. The sample period is all regularly scheduled FOMC meetings from 1/1/2000 to 3/19/2014, except that we drop the period from July 2008 through June 2009. For 2Y and 3Y yields and real forwards, the sample starts in January 2004. The sample size for the 2Y and 3Y yields and forwards is 74. The sample size for all other regressions is 106—the same observations from which the policy news shock is constructed. Robust standard errors are in parentheses.

Table D.3: Mean Reversion

Horizon (Trading Days)	Nominal Yields 2-Year	Nominal Yields 3-Year	Nominal Yields 5-Year	Real Yields 2-Year	Real Yields 3-Year	Real Yields 5-Year
1	1.10	1.06	0.73	1.06	1.02	0.64
	(0.34)	(0.39)	(0.21)	(0.28)	(0.31)	(0.19)
5	2.24	2.06	0.85	1.01	0.93	0.52
	(1.09)	(1.07)	(0.50)	(0.64)	(0.68)	(0.38)
10	2.39	2.20	0.22	1.35	1.20	0.28
	(1.07)	(1.05)	(0.80)	(0.55)	(0.57)	(0.53)
20	0.60	0.29	-0.01	0.88	0.43	0.04
	(1.22)	(1.16)	(1.11)	(0.95)	(0.94)	(0.79)
60	3.41	2.80	-0.17	1.96	1.72	-0.10
	(2.38)	(2.17)	(1.46)	(2.13)	(1.92)	(1.13)
125	9.42	8.02	3.20	6.16	5.22	2.47
	(1.78)	(1.61)	(1.98)	(2.86)	(2.50)	(1.44)
250	13.52	11.56	4.72	9.58	8.22	4.13
	(3.31)	(3.08)	(2.30)	(2.92)	(2.97)	(1.84)

Each estimate comes from a separate OLS regression. We regress the cumulative change in yields between the day before the FOMC announcement and 1, 5, 10, 20, 60, 125 and 250 trading days after the announcement on the policy news shock in the 30 minute interval surrounding the FOMC announcement. The first three columns present results for nominal zero coupon yields, and the next three columns present results for real zero coupon yields. The sample period is all regularly scheduled meetings from 1/1/2000 to 3/19/2014, except that we drop the period from July 2008 through June 2009. For 2Y and 3Y yields, the sample starts in January 2004. Going down the rows, the sample sizes for the 2Y and 3Y yields are 74, 73, 73, 73, 72, 69, and 65. The sample sizes for the 5Y yield are 106, 105, 105, 105, 104, 101, and 97. The policy news shock is constructe on the 2000-2014 sample used in Table 1. Newey-West standard errors with 4 lags are in parentheses.

estimates become very noisy as the event window becomes larger, there is little evidence that the effects on interest rates tend to dissipate over time. Indeed, in most cases, the point estimates appear to grow over time (though, again, the standard errors are quite large).

E A Conventional Model of Monetary Shocks

What do the empirical estimates in section 3 tell us about the economy? The conventional view of how monetary policy affects the economy can be decomposed into two parts. First, changes in nominal interest rates affect real interest rates. Second, changes in real interest rates affect output. The second of these components is a common feature of virtually all macroeconomic models and has nothing to do with monetary policy per se. In particular, both Neoclassical and New Keynesian models share the implication that changes in real interest rates affect output. In sharp contrast, Neoclassical and New Keynesian models have very different predictions regarding the extent to which changes in nominal interest rates caused by monetary policy can affect real interest rates. In a Neoclassical model, variation in nominal interest rates caused by monetary policy have *no* effect on the real interest rate, while in New Keynesian models, such movements in nominal interest rates can have large effects on real rates if prices are sufficiently sticky.

The evidence we present in section 3 shows that variation in nominal interest rates caused by monetary policy announcements does have large and persistent effects on real interest rates. In a conventional model of how monetary shocks affect the economy—i.e., one where monetary shocks only convey information about the future path of policy and don't change private sector views about other fundamentals of the economy—this evidence identifies key parameters governing the rigidity of prices. We can illustrate this very simply using the textbook New Keynesian model.

Consider a setting in which the behavior of households and firms can be described by the following Euler equation and Phillips curve:

$$\hat{x}_t = E_t\hat{x}_{t+1} - \sigma(\hat{\imath}_t - E_t\hat{\pi}_{t+1} - \hat{r}^n_t), \tag{5}$$

$$\hat{\pi}_t = \beta E_t\hat{\pi}_{t+1} + \kappa\zeta\hat{x}_t. \tag{6}$$

Hatted variables denote percentage deviations from steady state. The variable $\hat{x} = \hat{y}_t - \hat{y}^n_t$ denotes the "output gap"—the difference between actual output $\hat{y}_t$ and the "natural" level of output $\hat{y}^n_t$ that would prevail if prices were flexible— $\hat{\pi}_t$ denotes inflation, $\hat{\imath}_t$ denotes the gross return on a one-period, risk-free, nominal bond, and $\hat{r}^n_t$ denotes the "natural rate of interest." The parameter σ in the Euler equation denotes the intertemporal elasticity of substitution, while β denotes the subjective discount factor of households, κ and ζ denote nominal and real rigidities, respectively. Both the natural rate of output and the natural rate of interest are functions of exogenous shocks to tastes and technology. Appendix H presents a detailed derivation of these equations from primitive assumptions about tastes and technology. Woodford (2003) and Gali (2008) present textbook treatments.

Suppose this economy starts off at a zero-inflation steady state and is then disturbed by a monetary shock. Assuming that the monetary shock has no effect on output in the long run, we can solve the Euler equation—equation (5)—forward and get that the response of the output gap to the monetary shock is,

$$\hat{x}_t = -\sigma\sum_{j=0}^{\infty} E_t\hat{r}_{t+j} = -\sigma\hat{r}^{\ell}_t. \tag{7}$$

where $\hat{r}_{t+j}$ denotes the response of the short-term real interest rate at time $t+j$—i.e., $\hat{r}_{t+j} = \hat{\imath}_{t+j} -$

$E_{t+j}\hat{\pi}_{t+j+1}$—and $\hat{r}^{\ell}_t$ denotes the response of the long-run real interest rate. Notice that $\hat{r}^n_t = 0$ in this case since the monetary shock has no effect on the natural rate of interest.

Similarly, we can solve forward the Phillips curve—equation (6)—and get that the response of inflation to the monetary shock is

$$\hat{\pi}_t = \kappa\zeta \sum_{j=0}^{\infty} \beta^j E_t \hat{x}_{t+j}. \tag{8}$$

Combining equations (7) and (8), we get a relationship between the response of inflation and the response of the real interest rates to the monetary shock:

$$\hat{\pi}_t = -\kappa\zeta\sigma \sum_{j=0}^{\infty} \beta^j E_t \hat{r}^{\ell}_{t+j}. \tag{9}$$

Recall that in section 3 we estimate the response of inflation and real interest rates to a monetary shock. These are exactly the two responses that appear in equation (9). Equation (9) therefore shows that in the textbook New Keynesian model the relative size of the response of inflation and real interest rates pins down the magnitude of the parameter triplet $\kappa\zeta\sigma$. Viewed through the lens of this model, the fact that we estimate a small response of inflation relative to the response of the real interest rate implies that either: 1) the Phillips curve must be very flat ($\kappa\zeta$ small), implying a lot of nominal and real rigidities, or 2) output must be very unresponsive to the real interest rate (σ small), or both.

Notice that in reaching these conclusions we do not need to fully specify the monetary policy rule. The only assumption we need to make about monetary policy is that monetary shocks do not have long-run effects on output. This is true of most common specifications of monetary policy rules used in the literature. In this respect, the conclusions reached above are quite robust.

Even so, let's consider whether this argument continues to hold even if the monetary shock leads to a shift in the long-run inflation target of the central bank (and therefore the long-run inflation rate). In this case, equation (9) becomes

$$\hat{\pi}_t = -\kappa\zeta\sigma \sum_{j=0}^{\infty} \beta^j E_t \hat{r}^{\ell}_{t+j} + \hat{\pi}_{\infty}, \tag{10}$$

where $\hat{\pi}_{\infty}$ denotes the change in the long-run inflation rate. The case we consider above assumed that $\pi_{\infty} = 0$. Even if this term is non-zero, however, it is important to recognize that it affects inflation in *every* period after the shock. Hence, it would not change the slope of the response of expected inflation. The extra term *does* have the potential to lead to a larger response of inflation to a monetary shock than in our baseline model. Empirically, however, the response of expected inflation to the monetary shock already appears to be very small. Adding this feature to the model would further increase the degree of rigidities we estimate in the data, and therefore, the degree of monetary non-neutrality.

In the analysis above, we did rely heavily on the conventional view of monetary shocks that they convey information only about the future path of policy but don't change private sector views about other fundamentals of the economy. In this view, monetary shocks may occur because the private sector is learning about the preferences of the policymakers, or because the private sector is learning about the policymaker's model of the world, or because the private sector is learning about the policymaker's views on the state of the economy. Crucially, however, the announcement by the policymaker cannot lead the private sector to update its own views about the state of the economy or the model of the world. If it does, the monetary shocks contains an additional "information effect."

If FOMC announcements affect not only beliefs about future monetary policy but also beliefs about future natural rates of interest, the conclusions reached above regarding what we can learn from the empirical evidence presented in section 3 can change dramatically. In this case, equation (7) becomes

$$\hat{x}_t = -\sigma \sum_{j=0}^{\infty} E_t(\hat{r}_{t+j} - \hat{r}^n_{t+j}) = -\sigma(\hat{r}^\ell_t - \hat{r}^{n\ell}_t), \tag{11}$$

where $\hat{r}^{n\ell}_t$ denotes the response to the monetary announcement of private sector beliefs about the long-term natural rate of interest, and equation (9) becomes

$$\hat{\pi}_t = -\kappa\zeta\sigma \sum_{j=0}^{\infty} \beta^j E_t(\hat{r}^\ell_{t+j} - \hat{r}^{n\ell}_t). \tag{12}$$

It is important to recognize that private sector behavior depends on private sector beliefs about the future path of the natural rate. The variables $\hat{r}^n_{t+j}$ and $\hat{r}^{n\ell}_t$ denote the response of private sector beliefs about natural rates, and $\hat{r}_{t+j}$ and $\hat{r}^\ell_{t+j}$ denote the response of private sector beliefs about actual real rates.

Notice that allowing for information effects, the response of the output gap and inflation to a monetary announcement is not determined by the response of real interest rates but rather by the response of the real interest rate *gap*—i.e., the gap between real interest rates and the natural rate of interest. This means that changes in real interest rates will not have as large effects on output and inflation if FOMC announcements have information effects since the movement in the interest rate gap will be only some fraction of the overall movement in interest rates. It also means that we will estimate larger values of the parameter triplet $\kappa\zeta\sigma$—i.e., smaller values of nominal and real rigidities (for a given value of the IES)—since the sum on the right-hand-side of equation (12) will be smaller than if we ignored information effects.

F Expected Output Growth Regressions

The regressions in Tables 3 and A.5 are of the form

$$\Delta s_{t,t-1} = \alpha + \gamma \Delta i_{t-1} + \epsilon_t \tag{13}$$

with the policy news shock as the independent variable. In Table 3, the dependent variable is

$$\Delta s_{t,t-1} = \frac{gy_{t,q(t)+1} + gy_{t,q(t)+2} + gy_{t,q(t)+3}}{3} - \frac{gy_{t-1,q(t)+1} + gy_{t-1,q(t)+2} + gy_{t-1,q(t)+3}}{3} \tag{14}$$

where $gy_{t,q(t)+j}$ denotes the average forecast made in month t about output growth in quarter $q(t)+j$, where $q(t)$ is the quarter that month t belongs to. For example, t might be September 2008, in which case $q(t)$ is the third quarter of 2008, $q(t)+2$ is the first quarter of 2009, and $gy_{t,q(t)+2}$ is the average forecast made in September 2008 about the value of output growth in the first quarter of 2009. In Table A.5, the dependent variable is

$$\Delta s_{t,t-1} = gy_{t,q(t)+j} - gy_{t-1,q(t)+j} \tag{15}$$

for $j \in \{0, 1, ..., 7\}$.

G Greenbook Evidence

If Fed information is important, one might expect that contractionary monetary shocks would disproportionately occur when the Fed is more optimistic than the private sector about the state of the economy. The top panel of Table G.1 tests this proposition using the Fed's Greenbook forecast about output growth as a measure of its optimism about the economy.[8] We report estimates from

[8] The staff of the Board of Governors has presented the FOMC with analysis and forecasts of the US economy in the Greenbook (now, the Tealbook) since 1965. Conveniently, both the Greenbook and Blue Chip datasets make forecasts of the same variable: annualized real GDP growth. The Greenbook forecasts are finalized one week before each FOMC meeting.

Table G.1: Is Fed Information Reflected in Greenbook Forecasts?

Horizon (q):	-1	0	1	2	3	4	5	6	7
Does Fed Relative Optimism Explain Monetary Shocks?									
β	--	1.19	1.01	1.21	1.00	1.20	1.89	3.10	1.88
	--	(0.55)	(0.74)	(0.69)	(0.77)	(0.90)	(1.10)	(1.14)	(1.64)
N	--	90	90	90	90	90	66	42	22
Does Fed Relative Optimism Reverse in Response to Monetary Shocks?									
β	-7.26	-4.07	-0.45	-0.87	-0.46	-1.66	-3.58	-1.34	-3.04
	(3.63)	(1.80)	(1.53)	(1.30)	(1.08)	(1.11)	(1.31)	(1.30)	(2.44)
N	24	89	89	89	89	76	55	32	8

Each estimate comes from a separate OLS regression. In the first panel, we regress the policy news shock (scaled by 100) on the difference in forecasts about output growth q quarters ahead between the Fed's Greenbook forecast and the Blue Chip forecast. Since the Blue Chip forecasts are available at a monthly frequency, we construct a corresponding monthly measure of our policy news shock. In particular, we use any policy news shock that occurs over the month except for those that occur in the first week (because we do not know whether these occurred before or after the survey response). In the second panel, we regress the change in the difference between the Greenbook and Blue Chip forecast of output growth q quarters ahead on the news policy shock. The change is between the month of the policy shock and the month of the subsequent FOMC meeting. See Appendix F for details. The sample period is all regularly scheduled FOMC meetings from January 1995 to December 2009, except that we exclude the period from July 2008 through June 2009 and the aforementioned first-week meetings. The policy news shocks are constructed over the 1995-2014 sample used in Table A.5. Robust standard errors are in parentheses.

the following regression:

$$\text{policy news shock}_t = \alpha + \beta \left(\Delta y^{GB}_{t,q} - \Delta y^{BC}_{t,q} \right) + \varepsilon_t, \tag{16}$$

where $\Delta y^{GB}_{t,q}$ is the Greenbook forecast of quarterly output growth (annualized) q quarters in the future made in month t, and $\Delta y^{BC}_{t,q}$ is the corresponding Blue Chip forecast. In words, we regress our policy news shock on the contemporaneous difference between the Greenbook and Blue Chip forecasts about real GDP growth at various horizons. The positive coefficients reported in the top panel of Table G.1 indicate that our policy news shocks tend to be positive (i.e., indicate a surprise increase in interest rates) when the Greenbook forecast about current and future real GDP growth is higher than the corresponding Blue Chip forecast.

We furthermore find that the difference between Greenbook and Blue Chip forecasts tends to narrow after our policy news shocks occur. This suggests that private sector forecasters may update their forecasts based on information they gleam from FOMC announcements. Building on the work of Romer and Romer (2000), we estimate the following regression:

$$\left[\left(\Delta y^{GB}_{t+1,q} - \Delta y^{BC}_{t+1,q}\right) - \left(\Delta y^{GB}_{t,q} - \Delta y^{BC}_{t,q}\right)\right] = \alpha + \beta \text{policy news shock}_t + \varepsilon_{t+1}, \tag{17}$$

where time $t+1$ is the month of the next FOMC meeting. In words, we assess whether our policy news shocks forecast a change in the difference between the Greenbook and the Blue Chip forecasts of output growth. The results of this regression are reported in the bottom panel of Table G.1. We find that a positive policy news shock forecasts a fall in the Greenbook forecast relative to the Blue Chip forecast (or equivalently a rise in the Blue Chip forecast relative to the Greenbook forecast). This change in statistically significant for the nowcast ($q = 0$) and for one of the longer-term forecasts ($q = 5$) but not statistically significant for the other horizons. Since positive monetary shocks tend to be associated with the Greenbook forecast being above the Blue Chip, the fact that the estimates are negative in this regression indicates that, indeed, our policy news shocks are associated with a narrowing in the discrepancy between Fed and private sector views on the economy.

H Micro-Foundations for Our Model

This section lays out micro-foundations for the New Keynesian business cycle model we use in the paper. We do this in two steps. First we present a version of the model without internal habit and a backward-looking term in the Phillips curve. Then in sections H.4-H.6, we show how the model is modified to include internal habit and a backward-looking term in the Phillips curve. We end this appendix with a discussion of the determination of the natural rate of output and productivity in the full model. We note that none of the derivations in this section depend on whether there is an information effect of not. See Woodford (2003) and Gali (2008) for thorough expositions of New Keynesian models.

H.1 Households

The economy is populated by a continuum of household types indexed by x. A household's type indicates the type of labor supplied by that household. Households of type x seek to maximize their utility given by

$$E_0 \sum_{t=0}^{\infty} \beta^t [u(C_t, \xi_t) - v(L_t(x), \xi_t)], \tag{18}$$

where β denotes the household's subjective discount factor, C_t denotes household consumption of a composite consumption good, $L_t(x)$ denotes household supply of differentiated labor input x, and ξ_t denotes a vector of preference shocks. There are an equal (large) number of households of each type. The composite consumption good in expression (18) is an index given by

$$C_t = \left[\int_0^1 c_t(z)^{\frac{\theta-1}{\theta}} dz\right]^{\frac{\theta}{\theta-1}}, \tag{19}$$

where $c_t(z)$ denotes consumption of products of variety z. The parameter $\theta > 1$ denotes the elasticity of substitution between different varieties.

Households have access to complete financial markets. Households of type x face a flow budget constraint given by

$$P_t C_t + E_t[M_{t,t+1} B_{t+1}(x)] \leq B_t(x) + W_t(x) L_t(x) + \int_0^1 \Xi_t(z) dz - T_t, \tag{20}$$

where P_t is a price index that gives the minimum price of a unit of the consumption good C_t, $B_{t+1}(x)$ is a random variable that denotes the state contingent payoff of the portfolio of financial securities held by households of type x at the beginning of period $t+1$, $M_{t,t+1}$ is the stochastic discount factor that prices these payoffs in period t,[9] $W_t(x)$ denotes the wage rate received by households of type x in period t, $\Xi_t(z)$ denotes the profits of firm z in period t, and T_t is a lump-sum tax levied by the government. To rule out Ponzi schemes, household debt cannot exceed the present value of future income in any state of the world.

Households face a decision in each period about how much to spend on consumption, how many hours of labor to supply, how much to consume of each differentiated good produced in the economy and what portfolio of assets to purchase. Optimal choice regarding the trade-off between current consumption and consumption in different states in the future yields the following consumption Euler equation:

$$\frac{u_c(C_{t+j}, \xi_{t+j})}{u_c(C_t, \xi_t)} = \frac{M_{t,t+j}}{\beta^j} \frac{P_{t+j}}{P_t} \tag{21}$$

as well as a standard transversality condition. The notation u_c denotes the partial derivate of the function u with respect to C_t. We use analogous notation for other partial derivatives below. Equation (21) holds state-by-state for all $j > 0$. Optimal choice regarding the intratemporal trade-off

[9] The stochastic discount factor $M_{t,t+1}$ is a random variable over states in period $t+1$. For each such state it equals the price of the Arrow-Debreu asset that pays off in that state divided by the conditional probability of that state. See Cochrane (2005) for a detailed discussion.

between current consumption and current labor supply yields a labor supply equation:

$$\frac{v_\ell(L_t(x), \xi_t)}{u_c(C_t, \xi_t)} = \frac{W_t(x)}{P_t}. \tag{22}$$

Households optimally choose to minimize the cost of attaining the level of consumption C_t. This implies the following demand curves for each of the differentiated products produced in the economy:

$$c_t(z) = C_t \left(\frac{p_t(z)}{P_t} \right)^{-\theta}, \tag{23}$$

where $p_t(z)$ denotes the price of product z and

$$P_t = \left[\int_0^1 p_t(z)^{1-\theta} dz \right]^{\frac{1}{1-\theta}}. \tag{24}$$

H.2 Firms

There are a continuum of firms indexed by z in the economy. Firm z specializes in the production of differentiated good z, the output of which we denote $y_t(z)$. For simplicity, labor is the only variable factor of production used by firms. Each firm is endowed with a fixed, non-depreciating stock of capital. The production function of firm z is

$$y_t(z) = A_t f(L_t(z)), \tag{25}$$

where A_t denotes aggregate productivity. The function f is increasing and concave. It is concave because there are diminishing marginal return to labor given the fixed amount of other inputs employed at the firm. We follow Woodford (2003) in introducing heterogeneous labor markets. Each firm belongs to an industry x. There are many firms in each industry. The goods in industry x are produced using labor of type x and all firms in industry x change prices at the same time. This heterogeneous labor market structure is a strong source of real rigidities in price setting.

Firm z acts to maximize its value,

$$E_t \sum_{j=0}^{\infty} M_{t,t+j} [p_{t+j}(z) y_{t+j}(z) - W_{t+j}(x) L_{t+j}(z)]. \tag{26}$$

Firm z must satisfy demand for its product given by equation (23). Firm z is therefore subject to the following constraint:

$$C_t\left(\frac{p_t(z)}{P_t}\right)^{-\theta} \leq A_t f(L_t(z)). \tag{27}$$

Firm z takes its industry wage $W_t(x)$ as given. Optimal choice of labor demand by the firm is given by

$$W_t(x) = A_t f_\ell(L_t(z)) S_t(z), \tag{28}$$

where $S_t(z)$ denotes the firm's nominal marginal cost (the Lagrange multiplier on equation (27) in the firm's constrained optimization problem).

Firm z can reoptimize its price with probability $1-\alpha$ as in Calvo (1983). With probability α, it must keep its price unchanged. Optimal price setting by firm z in periods when it can change its price implies

$$p_t(z) = \frac{\theta}{\theta-1} E_t \sum_{j=0}^{\infty} \frac{\alpha^j M_{t,t+j} y_{t+j}(z)}{\sum_{k=0}^{\infty} \alpha^k M_{t,t+k} y_{t+k}(z)} S_{t+j}(z). \tag{29}$$

Intuitively, the firm sets its price equal to a constant markup over a weighted average of current and expected future marginal cost.

H.3 A Linear Approximation of Private Sector Behavior

We seek a linear approximation of the equation describing private sector behavior around a zero-growth, zero-inflation steady state. We start by deriving a log-linear approximation for the consumption Euler equation that related consumption growth and a one-period, riskless, nominal bond. This equation takes the form $E_t[M_{t,t+1}(1+i_t)] = 1$, where i_t denotes the yield on a one-period, riskless, nominal bond. Using equation (21) to plug in for $M_{t,t+1}$ and rearranging terms yields

$$E_t\left[\beta U_c(C_{t+1}, \xi_{t+1}) \frac{P_t}{P_{t+1}}\right] = \frac{U_c(C_t, \xi_t)}{1+i_t}. \tag{30}$$

The zero-growth, zero-inflation steady state of this equation is $\beta(1+\bar{\imath}) = 1$. A first order Taylor series approximation of equation (30) around this steady state is

$$\hat{c}_t = E_t \hat{c}_{t+1} - \sigma(\hat{\imath}_t - E_t \hat{\pi}_{t+1}) - \sigma E_t \Delta \hat{\xi}_{ct+1}, \tag{31}$$

where $\hat{c}_t = (C_t - C)/C$, $\hat{\pi}_t = \pi_t - 1$, $\hat{\imath}_t = (1 + i_t - 1 - \bar{\imath})/(1+\bar{\imath})$, and $\hat{\xi}_{ct} = (U_{\xi c}/U_c)(\xi_t - 1)$. The parameter $\sigma = -U_c/(U_{cc}C)$ denotes the intertemporal elasticity of substitution of households.

We next linearize labor demand, labor supply, and the production function and combine these equations to get an expression for the marginal costs in period $t+j$ of a firm that last changed its price in period t. Let $\ell_{t,t+j}(x)$ denote the percent deviation from steady state in period $t+j$ of hours worked for workers in industry x that last was able to change prices in period t. Let other industry level variables be defined analogously. We assume that $f(L_t(x)) = L_t^a(x)$.

A linear approximation of labor demand—equation (28)—in period $t+j$ for industry x that was last able to change its prices in period t is then

$$\hat{w}_{t,t+j}(x) = \hat{a}_{t+j} - (1-a)\hat{\ell}_{t,t+j}(x) + \hat{s}_{t,t+j}(x), \tag{32}$$

where $\hat{w}_{t,t+j}(x)$ and $\hat{s}_{t,t+j}(x)$ denote the percentage deviation of real wages and real marginal costs, respectively, from their steady state values.

A linear approximation of labor supply—equation (22)—in period $t+j$ for industry x that was last able to change its prices in period t is

$$\hat{w}_{t,t+j}(x) = \eta^{-1}\hat{\ell}_{t,t+j}(x) + \sigma^{-1}\hat{c}_{t+j} + \hat{\xi}_{\ell,t+j} - \hat{\xi}_{c,t+j}, \tag{33}$$

where $\hat{\xi}_{\ell,t+j} = (V_{\ell\xi}/V_\ell)(\xi_t - 1)$. The parameter $\eta = V_\ell/(V_{\ell\ell}L)$ is the Frisch elasticity of labor supply.

A linear approximation of the production function—equation (25)—in period $t+j$ for industry x that was last able to change its prices in period t is

$$\hat{y}_{t,t+j}(x) = \hat{a}_{t+j} + a\hat{\ell}_{t,t+j}(x). \tag{34}$$

Combining labor demand and labor supply—equations (32) and (33)—to eliminate $\hat{w}_{t,t+j}(x)$ yields

$$\hat{s}_{t,t+j}(x) = (\eta^{-1} + 1 - a)\hat{\ell}_{t,t+j}(x) + \sigma^{-1}\hat{c}_{t+j} - \hat{a}_{t+j} + \hat{\xi}_{\ell,t+j} - \hat{\xi}_{c,t+j}.$$

Using the production function—equation (34)—to eliminate $\hat{\ell}_{t,t+j}(x)$ yields

$$\hat{s}_{t,t+j}(x) = \omega\hat{y}_{t,t+j}(x) + \sigma^{-1}\hat{c}_{t+j} - (\omega+1)\hat{a}_{t+j} + \hat{\xi}_{\ell,t+j} - \hat{\xi}_{c,t+j}, \tag{35}$$

where $\omega = (\eta^{-1} + 1 - a)/a$.

Taking logs of consumer demand—equation (23)—in period $t+j$ for industry x what was last able to change its prices in period t yields

$$\hat{y}_{t,t+j}(z) = -\theta \hat{p}_t(x) + \theta \sum_{k=1}^{j} \hat{\pi}_{t+k} + \hat{y}_{t+j}, \tag{36}$$

where we use the fact that $Y_t = C_t$ and $y_t(x) = c_t(x)$. Plugging this equation into equation (35) and again using the fact that $Y_t = C_t$ yields

$$\hat{s}_{t,t+j}(x) = -\omega\theta \hat{p}_t(x) + \omega\theta \sum_{k=1}^{j} \hat{\pi}_{t+k} + (\omega + \sigma^{-1})\hat{y}_{t+j} - (\omega+1)\hat{a}_{t+j} + \hat{\xi}_{\ell,t+j} - \hat{\xi}_{c,t+j} \tag{37}$$

It is useful to derive the level of output that would prevail if all prices were flexible. Since our model does not have any industry specific shocks (other than the opportunity to change prices), marginal costs of all firms are the same when prices are flexible. Firm price setting in this case yields $p_t(x) = \mu S_t$, where $\mu = \theta/(\theta - 1)$. This implies that all prices are equal and that $S_t/P_t = 1/\mu$. Since real marginal cost is a constant, we have $\hat{s}_t = 0$. The flexible price version of equation (37) is then

$$(\omega + \sigma^{-1})\hat{y}_t^n = (\omega+1)\hat{a}_t - \hat{\xi}_{\ell,t} + \hat{\xi}_{c,t}, \tag{38}$$

where we use the fact that output in all industries is the same under flexible prices and $\hat{y}_t = \hat{c}_t$ and denote the rate of output under flexible prices as y_t^n. We will refer to y_t^n as the natural rate of output.

Combining equations (37) and (38) yields

$$\hat{s}_{t,t+j}(x) = -\omega\theta \hat{p}_t(x) + \omega\theta \sum_{k=1}^{j} \hat{\pi}_{t+k} + (\omega + \sigma^{-1})(\hat{y}_{t+j} - \hat{y}_{t+j}^n) \tag{39}$$

We next linearize the price setting equation—equation (29). This yields:

$$\sum_{j=0}^{\infty} (\alpha\beta)^j \hat{p}_t(x) - \sum_{j=0}^{\infty} (\alpha\beta)^j E_t \hat{s}_{t,t+j}(x) - \sum_{j=1}^{\infty} (\alpha\beta)^j \sum_{k=1}^{j} E_t \hat{\pi}_{t+k} = 0.$$

Manipulation of this equation yields

$$\hat{p}_t(x) = (1 - \alpha\beta) \sum_{j=0}^{\infty} (\alpha\beta)^j E_t \hat{s}_{t,t+j}(x) + \alpha\beta \sum_{j=1}^{\infty} (\alpha\beta)^{j-1} E_t \hat{\pi}_{t+j}. \tag{40}$$

Using equation (39) to eliminate $\hat{s}_{t,t+j}(x)$ in equation (40) and manipulating the resulting equation yields

$$\hat{p}_t(x) = (1-\alpha\beta)\zeta \sum_{j=0}^{\infty} (\alpha\beta)^j E_t(\hat{y}_{t+j} - \hat{y}^n_{t+j}) + \alpha\beta \sum_{j=1}^{\infty} (\alpha\beta)^{j-1} E_t \hat{\pi}_{t+j}, \tag{41}$$

where $\zeta = (\omega + \sigma^{-1})/(1+\omega\theta)$.

A linear approximation of the expression for the price index—equation (24)—yields

$$\hat{\pi}_t = \frac{1-\alpha}{\alpha} \hat{p}_t(x). \tag{42}$$

Using this last equation to replace $\hat{p}_t(x)$ in equation (41) yields

$$\hat{\pi}_t = \kappa\zeta \sum_{j=0}^{\infty} (\alpha\beta)^j E_t(\hat{y}_{t+j} - \hat{y}^n_{t+j}) + (1-\alpha)\beta \sum_{j=1}^{\infty} (\alpha\beta)^{j-1} E_t \hat{\pi}_{t+j},$$

where $\kappa = (1-\alpha)(1-\alpha\beta)/\alpha$. Quasi-differencing the resulting equation yields

$$\hat{\pi}_t - \alpha\beta E_t \hat{\pi}_{t+1} = \kappa\zeta(\hat{y}_t - \hat{y}^n_t) + (1-\alpha)\beta E_t \hat{\pi}_{t+1},$$

which implies

$$\hat{\pi}_t = \beta E_t \hat{\pi}_{t+1} + \kappa\zeta(\hat{y}_t - \hat{y}^n_t). \tag{43}$$

Finally, we rewrite the household's Euler equation—equation (31) in terms of the output gap:

$$\hat{y}_t - \hat{y}^n_t = E_t(\hat{y}_{t+1} - \hat{y}^n_{t+1}) - \sigma(\hat{\imath}_t - E_t\hat{\pi}_{t+1} - r^n_t), \tag{44}$$

where r^n_t denotes the "natural rate of interest" as is given by

$$r^n_t = E_t \Delta\xi_{c,t+1} + \frac{1}{\sigma} E_t \Delta\hat{y}^n_{t+1}. \tag{45}$$

H.4 Household Behavior with Internal Habits

We now consider a case in which households form habits. Households of type x seek to maximize a utility function given by

$$E_0 \sum_{t=0}^{\infty} \beta^t [u(C_t - bC_{t-1}) - v(L_t(x))], \tag{46}$$

where the parameter b governs the strength of households' habit. We model household utility from consumption in period t as being affected by the amount that same household consumed in the previous period. Our model is therefore a model of "internal habit." Notice also that relative to the derivations above, we have eliminated reference to the preferences shocks ξ_t since they play no role in the analysis in the body of the paper.

Households face the same budget constraint as in the simple model (equation (20)). They also face the same no-Ponzi condition as in the simple model. Maximization of utility subject to these constraints yields the following consumption Euler equation and labor supply equation:

$$\frac{\Lambda_{t+j}}{\Lambda_t} = \frac{M_{t,t+j}}{\beta^j}\frac{P_{t+j}}{P_t}, \tag{47}$$

$$\frac{v_\ell(L_t(x),\xi_t)}{\Lambda_t} = \frac{W_t(x)}{P_t}, \tag{48}$$

where Λ_t denotes marginal utility from consumption at time t and is given by

$$\Lambda_t = u_c(C_t - bC_{t-1}) - b\beta E_t u_c(C_{t+1} - bC_t). \tag{49}$$

H.5 Firm Price Setting with Inflation Inertia

In the simple model presented above, we assume that prices are either reoptimized (with probability $1-\alpha$), or remain fixed (with probability α). As is well-known, this formulation yields a Phillips curve that implies that inflation reacts rapidly to news about future economic developments. Our empirical evidence suggests that inflation responds very gradually to news about future economic conditions. To be able to match this aspect of our evidence, we now follow Christiano, Eichenbaum, and Evans (2005) in considering a formulation of price setting in which firms index the price of the good they produce to past inflation whenever they don't reoptimize the price. This formulation makes inflation sluggish.

Firm z can reoptimize its price with probability $1-\alpha$ as in Calvo (1983). With probability α, it sets its price according to the following simple rule

$$p_t(z) = \frac{P_{t-1}}{P_{t-2}} p_{t-1}(z). \tag{50}$$

The firm's optimization problem is otherwise the same as in section H.2. Optimal price setting by firm z in periods when it can change its price implies

$$p_t(z) = \frac{\theta}{\theta-1} E_t \sum_{j=0}^{\infty} \frac{\alpha^j M_{t,t+j} y_{t+j}(z)}{\sum_{k=0}^{\infty} \alpha^k M_{t,t+k}(P_{t+j-1}/P_{t-1}) y_{t+k}(z)} S_{t+j}(z). \tag{51}$$

The firm's labor demand equation is the same as in section H.2.

H.6 A Linearization of Private Sector Behavior in the Augmented Model

We seek a linear approximation of the equations describing private sector behavior with internal habits and price indexation. As before, we start by deriving a log-linear approximation for the consumption Euler equation that related consumption growth and a one-period, riskless, nominal bond. This equation may be written

$$E_t\left[\beta\Lambda_{t+1}\frac{P_t}{P_{t+1}}\right]=\frac{\Lambda_t}{1+i_t}. \tag{52}$$

The zero-growth, zero-inflation steady state of this equation is $\beta(1+\bar{\imath})=1$. A first order Taylor series approximation of equation (30) around this steady state is

$$\hat{\lambda}_t=E_t\hat{\lambda}_{t+1}+(\hat{\imath}_t-E_t\hat{\pi}_{t+1}), \tag{53}$$

where $\hat{\lambda}=(\Lambda_t-\Lambda)/\Lambda$.

A linear approximation of labor supply—equation (48)—in period $t+j$ for industry x that was last able to change its prices in period t is

$$\hat{w}_{t,t+j}(x)=\eta^{-1}\hat{\ell}_{t,t+j}(x)-\hat{\lambda}_{t+j}. \tag{54}$$

A linear approximation of marginal utility of consumption—equation (49)—is given by

$$\hat{\lambda}_t=-(1+b^2\beta)\sigma_c\hat{c}_t+b\sigma_c\hat{c}_{t-1}+b\beta\sigma_cE_t\hat{c}_{t+1}, \tag{55}$$

where $\sigma_c=-\sigma^{-1}/((1-b)(1-b\beta))$.

Combining equation (54) with equations (32) (without the preference shock) and equation (34) yields

$$\hat{s}_{t,t+j}(x)=\omega\hat{y}_{t,t+j}(x)-\hat{\lambda}_{t+j}-(\omega+1)\hat{a}_{t+j}. \tag{56}$$

With price indexation, consumer demand in period $t+j$ in an industry x that last changed its price in period t is

$$y_{t+j}(x)=\left(\frac{p_t(x)}{P_{t+j}}\frac{P_{t+j-1}}{P_{t-1}}\right)^{-\theta}Y_{t+j}. \tag{57}$$

A linear approximation of this equation is

$$\hat{y}_{t,t+j}(z) = -\theta\hat{p}_t(x) + \theta\sum_{k=1}^{j}\hat{\pi}_{t+k} - \theta\sum_{k=0}^{j-1}\hat{\pi}_{t+k} + \hat{y}_{t+j}. \tag{58}$$

Plugging this into equation (56) yields

$$\hat{s}_{t,t+j}(x) = -\omega\theta\hat{p}_t(x) + \omega\theta\sum_{k=1}^{j}\hat{\pi}_{t+k} - \omega\theta\sum_{k=0}^{j-1}\hat{\pi}_{t+k} + \omega\hat{y}_{t+j} - \hat{\lambda}_{t+j} - (\omega+1)\hat{a}_{t+j}. \tag{59}$$

As in the simple model considered above, it is useful to derive a relationship between the natural level of output and marginal cost and the exogenous shocks in the model. With flexible prices all firms set the same price. In this case we have $p_t(x) = \mu S_t$ and $\hat{s}_t = 0$. This implies that the flexible price version of equation (59) is

$$\omega\hat{y}^n_{t+j} - \hat{\lambda}^n_{t+j} = (\omega+1)\hat{a}_{t+j}. \tag{60}$$

Combining equations (59) and (60) yields

$$\hat{s}_{t,t+j}(x) = -\omega\theta\hat{p}_t(x) + \omega\theta\sum_{k=1}^{j}\hat{\pi}_{t+k} - \omega\theta\sum_{k=0}^{j-1}\hat{\pi}_{t+k} + \omega(\hat{y}_{t+j} - \hat{y}^n_{t+j}) - (\hat{\lambda}_{t+j} - \hat{\lambda}^n_{t+j}). \tag{61}$$

We next linearize the price setting equation—equation (51). This yields:

$$\sum_{j=0}^{\infty}(\alpha\beta)^j\hat{p}_t(x) - \sum_{j=0}^{\infty}(\alpha\beta)^jE_t\hat{s}_{t,t+j}(x) - \sum_{j=1}^{\infty}(\alpha\beta)^j\sum_{k=1}^{j}E_t\hat{\pi}_{t+k} + \sum_{j=1}^{\infty}(\alpha\beta)^j\sum_{k=0}^{j-1}E_t\hat{\pi}_{t+k} = 0.$$

Manipulation of this equation yields

$$\hat{p}_t(x) = (1-\alpha\beta)\sum_{j=0}^{\infty}(\alpha\beta)^jE_t\hat{s}_{t,t+j}(x) + \alpha\beta\sum_{j=1}^{\infty}(\alpha\beta)^{j-1}E_t\hat{\pi}_{t+j} - \alpha\beta\sum_{j=0}^{\infty}(\alpha\beta)^jE_t\hat{\pi}_{t+j}. \tag{62}$$

Using equation (61) to eliminate $\hat{s}_{t,t+j}(x)$ in equation (62) and manipulating the resulting equation yields

$$\hat{p}_t(x) = (1-\alpha\beta)\hat{\zeta}\sum_{j=0}^{\infty}(\alpha\beta)^jE_t[\omega\hat{x}_{t+j} - \hat{\lambda}_{xt+j}] + \alpha\beta\sum_{j=1}^{\infty}(\alpha\beta)^{j-1}E_t\hat{\pi}_{t+j} - \alpha\beta\sum_{j=0}^{\infty}(\alpha\beta)^jE_t\hat{\pi}_{t+j}, \tag{63}$$

where $\hat{\lambda}_{xt} = \hat{\lambda}_t - \hat{\lambda}^n_t$ and $\hat{\zeta} = 1/(1+\omega\theta)$.

A linear approximation of the expression for the price index—equation (24)—in the case with indexation between price changes yields

$$\hat{\pi}_t - \hat{\pi}_{t-1} = \frac{1-\alpha}{\alpha}\hat{p}_t(x). \tag{64}$$

Using this last equation to replace $\hat{p}_t(x)$ in equation (63) yields

$$\hat{\pi}_t - \hat{\pi}_{t-1} = \kappa\hat{\zeta}\sum_{j=0}^{\infty}(\alpha\beta)^j E_t[\omega\hat{x}_{t+j} - \hat{\lambda}_{xt+j}] + (1-\alpha)\beta\sum_{j=1}^{\infty}(\alpha\beta)^{j-1}E_t\hat{\pi}_{t+j} - (1-\alpha)\beta\sum_{j=0}^{\infty}(\alpha\beta)^j E_t\hat{\pi}_{t+j}.$$

Quasi-differencing this equation yields

$$(\hat{\pi}_t - \hat{\pi}_{t-1}) - \alpha\beta(E_t\hat{\pi}_{t+1} - \hat{\pi}_t) = \kappa\hat{\zeta}(\omega\hat{x}_{t+j} - \hat{\lambda}_{xt+j}) + (1-\alpha)\beta(E_t\hat{\pi}_{t+1} - \hat{\pi}_t),$$

which implies

$$\Delta\hat{\pi}_t = \beta E_t\Delta\hat{\pi}_{t+1} + \kappa\hat{\zeta}(\omega\hat{x}_{t+j} - \hat{\lambda}_{xt+j}). \tag{65}$$

Finally, we rewrite the household's Euler equation—equation (53) in terms of the marginal utility gap:

$$\hat{\lambda}_{xt} = E_t\hat{\lambda}_{xt+1} - \sigma(\hat{\imath}_t - E_t\hat{\pi}_{t+1} - r_t^n), \tag{66}$$

where r_t^n denotes the "natural rate of interest" as is given by

$$r_t^n = \frac{1}{\sigma}E_t\Delta\hat{\lambda}_{t+1}^n. \tag{67}$$

H.7 Determination of Natural Rate of Output and Productivity

Since the monetary shock affects private sector beliefs about the path of the natural rate of interest, it also affects the private sector's beliefs about the path of the natural rate of output. The solution to the following equation:

$$(1 + b\beta + b^2\beta)\hat{y}_{t+1}^n = b\beta E_t\hat{y}_{t+2}^n + (1 + b + b^2\beta)\hat{y}_t^n - b\hat{y}_{t-1}^n + \sigma_c^{-1}\psi\bar{r}_t \tag{68}$$

using our assumed initial response for the natural rate of output of $y_0^n = \psi\bar{r}_0$ yields a path for the natural rate of output that is consistent with the path of the natural rate of interest implied by our assumption about Fed information, i.e., $r_t^n = \psi\bar{r}_t$. This can be verified by using the resulting path for the natural rate of output to construct a path for the natural rate of marginal utility according to equation (55) and then plugging the resulting path for the natural rate of marginal utility into equation (67). This will yield $r_t^n = \psi \bar{r}_t$.

The logic for this construction of the path of the natural rate of output is easier to comprehend in the textbook New Keynesian model without habit. Suppose $r_t^n = \psi \bar{r}_t$ and $y_0^n = \psi \bar{r}_0$ in that model and we are interested in constructing the path for the natural rate of output that is consistent with these assumptions. The consumption Euler equation in that model implies that $\hat{y}_t^n = E_t \hat{y}_{t+1}^n - \sigma \psi \bar{r}_t$. For this equation to hold, it must be that $\hat{y}_{t+1}^n = \hat{y}_t^n + \sigma \psi \bar{r}_t$. One can thus construct a path for the natural rate of output that is consistent with the desired path for the natural rate of interest by iterating forward $\hat{y}_{t+1}^n = \hat{y}_t^n + \sigma \psi \bar{r}_t$ with the initial condition $y_0^n = \psi \bar{r}_0$. The argument above, is the equivalent argument when households have internal habit.

Given the path for the natural rate of output that we construct above, one can construct a path for the response of private sector beliefs about productivity (the exogenous shock that we assume is driving variation in the natural rate of output and the natural rate of interest) by using equation (60). In the counterfactual, we assume that agents believe productivity is a random walk and then feed in a shock process for productivity that makes productivity follow the same path as in the actual case of the monetary shock.

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