Modeling Post-Crisis Monetary Policy

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Modeling Post-Crisis Monetary Policy

by

James Dean

Dissertation submitted to the
John Chambers College of Business and Economics
at West Virginia University
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy
in
Economics

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2022

Keywords: Monetary Policy, Macroeconomic Models, Quantitative Easing, Forward Guidance, Interest on Reserves

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Abstract

Modeling Post-Crisis Monetary Policy

by James Dean

Since 2008, the Federal Reserve has added tools to its policy toolkit, changed the framework it uses when setting policy, and modified the way it implements policy. This dissertation is comprised of three chapters, each focusing on how monetary policy has evolved with the addition of these new policies.

Chapter 1, co-authored with Scott Schuh, examines whether the Taylor Rule still adequately captures monetary policy. A Taylor Rule remains the consensus in macroeconomic models despite unconventional monetary policies (UMP) and the policy rate near zero in 2009-2015. We find structural breaks at 2007:Q3 in macro models with a shadow funds rate to control for UMP. Taylor Rule coefficients shift back toward pre-1984 estimates (relative increase in output gap weight). Significant breaks also occurred in non-policy parameters, altering shocks, dynamics, and output gaps. Results are similar with the effective funds rate, so either breaks are not due to UMP or the shadow rate is an insufficient specification of UMP in macro models.

Chapter 2 builds on this finding by incorporating the term structure and the Fed’s new average inflation targeting (AIT) framework into the DSGE model of Sims and Wu (2020) with an occasionally binding zero-lower bound. When agents know the Fed’s exact policy rule, AIT stabilizes inflation and household utility compared to standard inflation targeting. Inflation is most stable, and household utility is highest, when the average window is 8 and 16 quarters, respectively. The Fed has not revealed their lag structure of AIT, and this imperfect information affects the model’s results. If agents don’t know the exact details of the policy, inflation is most stable when the Fed averages inflation over longer periods. Outcomes are always better when the Fed reveals the specific details about the policy.

Chapter 3 examines and critiques the literature surrounding interest on reserves (IOR) and how it changed the Fed’s interest rate policy implementation. I examine early theories around the conduct of IOR and its interaction with the fed funds market. I then discuss how the implementation of IOR has differed from these theories, and, through a simple model of the fed funds market, I show how IOR reshaped the market for reserves. Finally, I analyze modern challenges of IOR and monetary policy in an “abundant reserve” regime.
Acknowledgments

While my name is on this dissertation, its development and completion is the product of many fantastic people around me. First, this dissertation would not have been possible without Dr. Scott Schuh. Thank you, Scott, for your time, patience, encouragement, and commitment to my development. You have made me a better economist and, more importantly, a better human being. Further, I would like to thank Dr. Arabinda Basistha, Dr. Shuchiro Nishioka, and Dr. Peter Ireland for their frequent guidance and attentive ears. None of this would have been possible without each of your help and support. I am also thankful for Dr. Russell Dabbs, Dr. Stacy Patty, and others at Lubbock Christian University and the LCU Honors College. I would not have even considered pursuing a PhD without you.

Next, I am thankful for my parents, David and Kristi. The example you’ve set, the love you’ve provided, and the encouragement you’ve given are my foundation for growth, both professional and personal. I am grateful for my brothers and sister-in-law, Zach, Jason, and Jen. Your compassion, memes, and Sunday FaceTime have been an anchor of levity throughout graduate school. Thank you to my grandparents, Stan, Betty, and Katie, for your endless love.

Thank you to the graduate students at WVU, and especially to Alex Cardazzi and Keri Lawson. Friday Shawarma, Gene’s nights, Sunday Basketball, and porch beers have provided a constant reminder that academic achievement cannot be without fun and fulfillment. Finally, thank you to Heather Johnson. Your ebullience, heart, and belief in who I can be are a pillar of joy no matter what else is happening.
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2 Better On Average? Average Inflation Targeting with Unconventional Monetary Policy

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Chapter 1

Is the Taylor Rule Still an Adequate Representation of Monetary Policy in Macroeconomic Models?

1.1 Introduction

More than a decade after the Global Financial Crisis (GFC) and implementation of unconventional monetary policies (UMP), John Taylor’s (1993) interest rate rule remains the consensus specification of monetary policy in most macroeconomic models. Prominent examples include the benchmark New Keynesian DSGE model in “Rebuilding Macro Theory” (Vines and Wills, 2018); 150 structural models in the Macroeconomic Model Data Base (MMB); textbooks at all levels; and even recent innovations in macro models with monetary policy. The Federal Reserve Board still relies on a prototypical Taylor Rule for the federal funds rate in its primary macro model, FRB/US:

\[ i_t = \rho i_{t-1} + \left(1 - \rho \right) \left[ r + \pi_t + \phi_\pi \left( \pi_t - \pi^* \right) + \phi_x x_t \right] + \epsilon_t \]  

\[ (1.1) \]

1 A short list of innovations includes Gabaix (2020), Barnichon and Mesters (2021), Laurays et al. (2021), and Fuhrer (2017). For details on MMB see https://www.macromodelbase.com/.
where \( i_t \) is the nominal interest rate, \( r \) is the “natural” (equilibrium) real rate, \( \pi \) is inflation, \( \pi^* \) is target inflation, \( x_t \) is the output gap (Brayton et al., 2014); the Fed’s Estimated Dynamic Optimization (EDO) model adds the change in the output gap (Chung et al., 2010). While particular specifications vary, most macro models still include an equation close to this one.

The sufficiency of a single rule like equation 1.1 for monetary policy is being re-examined. For example, in his AEA Presidential Address, Bernanke (2020) notes that “old methods won’t do” when implementing policy, and that “[i]f monetary policy is to remain relevant, policymakers will have to adopt new tools, tactics, and frameworks” [emphasis added]. Introduction of markedly different UMP after 2007 raises questions about whether a single monetary policy instrument and rule like Taylor’s can adequately represent the full measure of modern monetary policy in macroeconomic models. On the other hand, Taylor (2021) still advocates the powerful simplicity of his original rule.

We address this question and the paper’s title by testing for structural breaks in Taylor Rule and non-policy parameters starting in 2007:Q3, the boundary between the Great Moderation (1984-2007) and the period between the GFC and COVID-19 pandemic (2008-2019).\(^2\) Identifying UMP is challenging, as explained in Rossi’s (2021) excellent survey. We use three benchmark macro models that do not include UMP but vary in size and degree of structural restrictions for robustness: 1) a VAR with modest restrictions; 2) the three-variable New Keynesian (NK) model of Clarida, Gali, and Gertler (1999, 2000); and 3) the DSGE model of Smets and Wouters (2007). Rossi (2021) focuses on reduced-form models like our VAR and other creative strategies for identifying monetary shocks. Like Carvahlo et al (2022), we add two structural models in search of more detailed identification and understanding, but use full-information estimation of entire macro models in search of breaks due to UMP.\(^3\)

\(^2\)The COVID-19 pandemic and recession precipitated additional unconventional policies, such as Fed purchases of commercial bonds and direct loans to small businesses, which are too new to properly evaluate and left for future research.

\(^3\)See Fuhrer, Moore, and Schuh (1995) and West and Wilcox (1996) for evidence on the superiority of FIML estimation to GMM and single-equation OLS.
Although focused on the break in 2007:Q3, the analysis covers 1960-2019 for completeness. Including the period before the Great Moderation (1960-1978) provides a comparison with earlier literature, starting with the finding by Bernanke and Mihov (1998) that no single policy variable (fed funds rate or nonborrowed reserves) explains monetary policy from 1965-1995 without a structural break. Previous studies with single-equation and VAR models typically find evidence of structural breaks occurring between 1979-1983 due to changes in the Fed’s operating procedure, preferences, and other factors influencing monetary policy. Likewise, introduction of sudden and sweeping UMP in 2007:Q3 suggests a new structural break, which is confirmed with an endogenous break test.

Unlike prior research, using the federal funds rate in the Taylor Rule after 2007:Q3 poses new econometric difficulties that must be addressed. The fed funds rate was stuck at the effective lower bound (ELB) for nearly seven years (2009-2015) so this truncation may bias inference for potentially all model parameters. Also, implementation of UMP introduced new government behaviors that likely affected structural equations of all models. To circumvent these problems, we use the “shadow” fed funds rate of Wu and Xia (2016); see also Krippner (2013) and Bauer and Rudebusch (2014). Using a shadow rate indirectly introduces elements of UMP via the term structure because Forward Guidance (FG) and Quantitative Easing (QE) affect longer term rates. Our strategy alters the nature of contemporary structural break tests relative to past research by including elements of the very object (UMP) the test seeks to identify. Consequently, the structural break test is a joint test of the Taylor Rule and sufficiency of the shadow rate specification of UMP.

Despite using a shadow fed funds rate, we find statistically and economically significant evidence of structural breaks in the parameters of the Taylor Rule and non-policy equations. The post-GFC Taylor Rule shows the Fed is less responsive to changes in both inflation and the output gap after 2008, more so the former. While breaks in Taylor Rule coefficients are larger than the small-sample estimation biases noted in Carvahlo et al (2021), the changes have economically

---

4See Table 1.1 below for prior papers documenting structural breaks in the Taylor Rule.
5Even prior to the GFC, some papers incorporated the effects of an explicit zero lower bound (ZLB) constraint on the monetary policy rate. For examples, see Furher and Madigan (1997) and McCallum (2000).
moderate implications for the macro models. This begs the question: given the large, unconventional nature of changes in monetary policy, why isn’t there clear evidence of a greater effect? Perhaps the reason is because changes emerged elsewhere in the models. Indeed, many aspects of the non-policy structure of the economy also changed significantly after 2007:Q3. For examples, agents became more sensitive to changes in the real interest rate and expected inflation; steady state growth and inflation fell; and the Phillips Curve flattened. Some of these breaks may be related to policy changes, as in the Lucas Critique (Lucas 1976). Other coefficient breaks likely are not directly related to monetary policy, although they could influence the setting of optimal policy as well. Perhaps most surprisingly, estimation using the effective fed funds rate gives similar results, albeit with higher persistence ($\rho$).

Structural breaks also manifest themselves in economically significant changes in three key characteristics of the estimated models beyond the parameters. Structural shocks estimated over subsamples exhibit change in their relative volatility and autoregressive properties, which influences estimation of the Taylor Rule (Carvahlo et al., 2022). After 2007:Q3, the variance and persistence of DSGE monetary shocks increased, and properties of other shocks changed as well. This follows the result in Fernández-Villaverde and Rubio-Ramírez (2010) that time series often exhibit changes in volatility over time, and that must be modeled to adequately take account of the data. The models’ dynamic properties (impulse responses) also vary across subsamples. Dynamic differences are less evident when all parameters are allowed to change, but counterfactual exercises holding either Taylor Rule or non-policy coefficients fixed at full-sample estimates show considerably larger differences across subsamples. After 2007:Q3, the DSGE output and inflation responses to monetary policy shocks reverted back their magnitudes before the Great Moderation, which now looks more like an outlier period. Finally, subsample breaks in DSGE coefficients significantly affect estimates of the model-consistent output gap. The full-sample output gap deviates significantly from the Congressional Budget Office (CBO) output gap used by the VAR and NK models. The break-adjusted DSGE output gap much more closely resembles the CBO gap.
Together, the results suggest that using a UMP proxy (shadow funds rate) in macro models may not sufficiently capture the richness of contemporary monetary policy for at least two reasons. First, the prevalence of breaks in non-policy structural parameters suggests that time-variation in aspects of the macro models is important but missing. Thus, it is difficult to tell whether the observed breaks reflect time-variation unrelated to UMP rather or are the effects of UMP. Perhaps the most likely time variation occurred in steady state output growth and the natural real rate of interest. Controlling for time-variation in these and other variables and equations is an important extension of the benchmark models necessary for more conclusive break tests.

A second concern is the models do not include explicit, comprehensive structure that fully incorporates UMP. This limitation may be leading to an omitted variables (and equations) problem that appears as structural breaks in the estimated parameters. The natural remedy is include explicit, comprehensive specifications of UMP in the macro models. Efforts to do so are emerging but still limited thus far. Introduction of FG after 2007:Q3 mainly has been modeled and estimated (or calibrated) as the addition of policy announcement shocks to the Taylor Rule.\textsuperscript{6} Modeling QE has occurred mainly in theoretical models that introduce banks and their balance sheets to capture bond holdings and bank reserve management.\textsuperscript{7} One promising paper that combines these two strands is Wu and Zhang (2019), which microfounds a central bank’s bond holdings in an effort to map unconventional policies into a single “shadow” fed funds rate to be used in a standard Taylor Rule. Estimated macro models with UMP would be better-suited to identify the effects of policy changes.

1.2 Previous Literature

Table 1.1 lists the main papers reporting evidence on structural breaks in the Taylor Rule. The structure of the Rule has stayed largely the same as the original specification except for the addition

\textsuperscript{6}For more on forward guidance, see Del Negro, et. al (2012), Bundick and Smith (2016), Campbell et. al (2017) and McKay et. al (2016).

\textsuperscript{7}For examples on modeling QE, see the Gerler and Karadi (2011, 2013) and Joyce et. al (2012).
of persistence \((i_t-1)\), allowance for output dynamics (growth rate or gap change), and variation in lags or other practical features as shown in Coibion and Gorodnichenko (2012).\(^8\) The literature contains a variety of different modeling and econometric methods used to estimate breaks in the Taylor Rule coefficients. However, the results tend to be broadly consistent across papers.

Regime-switching models and break point tests, like those in Estrella and Fuhrer (2003) and Duffy and Engle-Warnick (2004) consistently show a regime change somewhere in the late 1970s or early 1980s followed by another in the mid 1980s. This result follows closely with the traditional narrative that the Federal Reserve undertook a “Monetarist experiment” during this period, wherein the Fed targeted the growth of a monetary aggregate rather than an interest rate. Using a single-equation model, Bunzel and Enders (2010) find these regimes appear in the Taylor Rule as a regime characterized by strong output gap and inflation responses (1970s) followed by a regime characterized by gradual adjustment of the federal funds rate (post 1980s). However, Estrella and Fuhrer (2003) note that these regime changes could be caused by changes elsewhere in the economy that smaller, single-equation models cannot estimate. Further, as Carvalho et al. (2022) show, the estimation methodology is important to any examination of Taylor Rule coefficients. Any estimation of monetary policy is subject to an endogeneity issue, as the central bank influences and responds to changes in inflation and output. Nevertheless, Carvalho et al. (2022) find that simple OLS estimates of the Taylor Rule still outperform IV estimates while still producing largely consistent model dynamics.

Researchers also have attempted to find structural breaks in VAR models. Using a factor-augmented VAR, Bernanke and Mihov (1998) find that no simple policy variable fully captures monetary policy from 1965-1996. Instead, they find regime switches in the Fed’s operating procedure in roughly 1979 and 1982, similar to the single-equation break-point models. Using structural VARs, Primiceri (2005) and Sims and Zha (2006) find similar timing of the regime changes but emphasize they are characterised by changes in the variance of Taylor Rule coefficients, as well as changes in the coefficient point estimates. In essence, the structural VARs suggest that mone-

tary policy after the mid-1980s is characterized best by more consistent responses to output and inflation.


We extend this literature by using a representative sample of three multi-equation models to investigate whether an additional structural break occurred in 2007:Q3, as might be expected. For robustness and reassurance, we first replicate the finding of a structural break in the early-1980s, as shown in Table 1.2. Our results are consistent with previous papers based on model type: during the Great Moderation, the VAR shows a decline in the variance of the estimated parameters while the NK and DSGE models show greater responsiveness to inflation.
Table 1.1: Summary of structural break literature

<table>
<thead>
<tr>
<th>Paper</th>
<th>Sample</th>
<th>Break(s)</th>
<th>Taylor Rule Implications</th>
<th>Nonpolicy Implications</th>
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</thead>
<tbody>
<tr>
<td>Estrella and Fuhrer (2003)</td>
<td>1966-1997</td>
<td>early-1980s</td>
<td>backward looking models are more stable than forward looking</td>
<td>N/A</td>
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1.3 Models

We use three benchmark macro models to estimate the Taylor Rule and test for structural breaks. For robustness, the models vary in size (small- to medium-scale) and degree of structure (few to many cross-equation restrictions).

1.3.1 Taylor Rules

The models contain two slightly different variants of the Taylor Rule. The VAR and NK models include a simplified version of the FRB/US Taylor Rule (equation 1.1),

$$i_t = \rho i_{t-1} + (1 - \rho)\left[\phi_\pi (\pi_t - \pi^*) + \phi_x x_t\right] + \epsilon_t,$$

(1.2)

which assumes a (suppressed) constant equilibrium nominal rate ($r + \pi^*$). The output gap, $x_t = (y_t - y^{POT})$, uses potential output (POT) from the Congressional Budget Office.9 The DSGE model adds short-run feedback from the change in the output gap as Smets and Wouters (2007):

$$r_t^f = \rho r_{t-1}^f + (1 - \rho)\left[\phi_\pi ^x \pi_t + \phi_y (y_t - y_t^P)\right] + \phi \Delta y [ (y_t - y_t^P) - (y_{t-1} - y_{t-1}^P)] + \epsilon_t,$$

(1.3)

9See https://www.cbo.gov/data/budget-economic-data.
where \( r^f_t = i_t \) to momentarily sidestep notation conflict (SW use \( i \) for investment and \( r \) for the nominal rate); henceforth, \( i_t \) is the nominal rate unless noted otherwise. Equation (1.3) uses the DSGE concept of potential output, \( y^p \), which denotes the level that would prevail if prices were flexible and there were no markups. Estimates of \( \rho \) and the \( \phi \) parameters provide evidence on stability of the Taylor Rule across subsamples. In contrast, Carvahlo et al. (2022) estimate their models with a Taylor Rule in which the Fed only targets inflation, rather than inflation and the output gap.

Neither the Taylor Rules nor the macro models incorporate UMP. However, some papers have incorporated Forward Guidance (FG) into the Taylor Rule using the effective fed funds rate and FG shocks to the future policy rate as follows:

\[
i_t = \rho i_{t-1} + (1 - \rho)\left[\phi_\pi(\pi_t - \pi^*) + \phi_x x_t\right] + \epsilon_t^{MP} + \sum_{l=1}^{L} \epsilon_{t,t-l}^R
\]  

(1.4)

where \( \sum_{l=1}^{L} \epsilon_{t,t-l}^R \) are FG shocks to the interest rate at time \( l \), but realized at \( t - l \) and \( \epsilon_t^{MP} \) are the standard monetary shocks.\(^{10}\) A FG shock is the difference between actual \( i_t \) and the expected rate announced by the central bank at time \( t - l \). Thus, FG on future policy rates essentially extends the duration of the short-term rate at the ELB.\(^{11}\)

Although the FG-augmented Taylor Rule does not account explicitly for the quantitative easing (QE) portion of UMP, it is mathematically similar to the FG shock in the literature on QE and shadow federal funds rates. As noted by scholars from Black (1995) to Rossi (2021), the shadow rate is an option, i.e., the short-term interest rate implied by a model of the yield curve. Wu and Zhang (2019) provide a mapping of QE into a standard NK model through the shadow rate. To do this, they assume the shadow rate, \( s_t \), follows the Central Bank (CB) balance sheet according to:

\[
s_t = -\zeta(b_t^{CB} - b_{t-1}^{CB}) + \epsilon_t^{FG} + \epsilon_t^{MP}
\]  

(1.5)

\(^{10}\)See Del Negro et al. (2012), Campbell et al. (2012), and Cole (2021). This specification also is called “forecast targeting” by Svensson (2017). Research with such models find a “Forward Guidance puzzle” of excessively large responses to FG news. The shadow fed funds rate controls for the effects of FG.

\(^{11}\)See Section 7 for more discussion of the relationship between FG and UMP.
where $\zeta$ maps the shadow rate to the difference between bond holdings, $b_t^{CB}$, and their steady state level and $\epsilon_t^{FG}$ is forward guidance, and $\epsilon_t^{MP}$ is the difference between the actual and predicted shadow rates.

Figure 1.1 shows the shadow rate closely tracks Fed bond holdings with only three key deviations, which Wu and Zhang (2019) note coincide with the Fed’s changes in FG. The early 2010 deviation coincides with the Fed signaling it would unwind its lending facilities. The 2014 decline coincides with the Fed extending its forecasted duration of the ELB. And the early 2013 spike coincides with the “taper tantrum” and is presented as a traditional monetary shock. In other words, deviations of the shadow rate from the Fed’s balance sheet present themselves similarly to the FG shock.

Figure 1.1: The Wu-Xia Shadow Rate and the Fed’s bond holdings

In short, by using the shadow rate we avoid the need to include the forward guidance augmented Taylor Rule in our estimation because $s_t$ incorporates forward guidance. Moreover, $s_t$ also includes the effect of quantitative easing, allowing us to incorporate both aspects of unconventional monetary policy. Henceforth, we refer to the interest rate as $\hat{i}_t$ where:

$$\hat{i}_t = \min(i_t, s_t)$$

(1.6)
to economize on notation later. The advantage of using the shadow rate is it allows for uniform comparison of the stance of monetary policy across conventional and unconventional policy periods.

1.3.2 VAR Model

The VAR model is based on the three-variable vector, \( Z_t = [x_t, \pi_t, \hat{u}_t]' \) that includes the output gap, inflation (\( \pi_t \)) and sample-specific policy rate. Abstracting from constant terms, the structural form is

\[
B_0 Z_t = \sum_{i=1}^{k} B_i Z_{t-1} + u_t ,
\]

where the 3x1 vector of structural shocks, \( u_t \), is identified from the Cholesky decomposition

\[
B_0 = \begin{bmatrix}
1 & 0 & 0 \\
\kappa & 1 & 0 \\
(1 - \rho)\phi_x & (1 - \rho)\phi_\pi & 1
\end{bmatrix}
\]

with usual diagonal covariance matrix, \( \Sigma = u_t u'_t \). The ordering restrictions allow the output gap to respond only to its own innovations and hence move the slowest. Inflation responds contemporaneously to the output gap and its own innovations, while the Fed’s policy rate responds to shocks in both the output gap and inflation as in the standard Taylor Rule.

This ordering identification originated with Sims (1980) but still is central to Rossi’s (2021) contemporary analysis. Our modest structural extension imposes interest-rate smoothing by restricting \( \rho = \Gamma_{3,1} \), which is the (3,1) element of the first lag \( (k = 1) \) of the reduced-form coefficient matrix, \( \Gamma_1 = B_0^{-1}B_1 \).
1.3.3 New Keynesian (NK) Model

The three-equation NK model is from Clarida, Gali, and Gertler (1999, 2000) and uses the same variables as the VAR. In addition to the Taylor Rule in equation (1.2), the NK model imposes structural restrictions in the form of the IS equation and forward-looking Phillips Curve:

\[
x_t = \psi [\hat{r}_t - E_t \pi_{t+1}] + E_t x_{t+1} + \epsilon_{x,t} \tag{1.9}
\]

\[
\pi_t = \kappa x_t + \beta E_t \pi_{t+1} + \epsilon_{\pi,t} \tag{1.10}
\]

where \(\beta\) is the discount factor, \(\psi\) is the coefficient of relative risk aversion, and \(\kappa\) is the slope of the Phillips Curve. Structural shocks \(\epsilon_{x,t}, \epsilon_{\pi,t},\) and \(\epsilon_{i,t}\) follow an AR(1) process:

\[
\epsilon_{x,t} = \rho_x \epsilon_{x,t-1} + \eta_{x,t} \tag{1.11}
\]

\[
\epsilon_{\pi,t} = \rho_\pi \epsilon_{\pi,t-1} + \eta_{\pi,t} \tag{1.12}
\]

\[
\epsilon_{i,t} = \rho_i \epsilon_{i,t-1} + \eta_{i,t} \tag{1.13}
\]

where \(0 < \rho_{x,t}, \rho_{\pi,t}, \rho_{i,t} < 1\) capture the persistence of shocks and \(\eta_{x,t}, \eta_{\pi,t}, \eta_{i,t}\) are i.i.d. with zero mean and variances \(\sigma_x^2, \sigma_\pi^2, \) and \(\sigma_i^2,\) respectively. The model has nine parameters: six structural parameters \((\beta, \psi, \kappa, \rho, \phi_\pi, \phi_y)\) and three auxiliary parameters \((\rho_x, \rho_\pi, \rho_i)\).

1.3.4 DSGE Model

The medium-scale DSGE model is from Smets and Wouters (2007), which contains the full linearized version. In addition to the Taylor Rule in equation (1.3), the portion of the DSGE model
that most closely matches the NK model are the consumption Euler equation and expectations-augmented NK Phillips Curve:

\[ c_t = c_1 c_{t-1} + (1 - c_1) E_t c_{t+1} + c_2 (l_t - E_t l_{t+1}) - c_3 (i_t - E_t \pi_{t+1} + \varepsilon^P_t) \]  (1.14)

\[ \pi_t = \pi_1 \pi_{t-1} + \pi_2 E_t \pi_{t+1} - \pi_3 \mu^P_t + \varepsilon^P_t \]  (1.15)

where \( c_t \) is real consumption, \( l_t \) is hours worked, \( \mu^P_t \) is the price markup, and \( \varepsilon^b_t, \varepsilon^P_t \) are structural shocks. The \( c_i \) and \( \pi_i \) are parameters to be estimated.\(^{12}\)

The DSGE model is more comprehensive and imposes stronger cross-equation restrictions than the NK model. For example, the NK IS Curve (1.9) is obtained from the simplifying assumption that \( y_t = c_t \) in the forward-looking consumption Euler equation. The DSGE model does not impose this assumption but explicitly models the entire aggregate resource constraint. Similarly, the NK Phillips Curve (1.10) is the linearized form of the firm’s simplified exogenous pricing decision. The DSGE model adds backward-looking elements into the consumption Euler equation and Phillips Curve plus a price mark-up in addition to sticky price adjustment.

The DSGE model has other advantages. It is consistent with a steady-state growth path, incorporating investment decisions and the pricing and accumulation of capital into its optimization problems. The DSGE model also has a more complex stochastic environment with seven structural shocks (productivity, technology, risk premium, spending, monetary, price-markup, and wage-markup) compared with three (demand, cost-push, and monetary), allowing richer and more flexible estimation of the effects of monetary policy.

\(^{12}\)For a more comprehensive summary of the SW DSGE model, see Chung, Herbst, and Kiley (2015).
1.4 Econometric Specifications

Most data used in this paper come from the FRED database created by the Federal Reserve Bank of St. Louis. The VAR and NK models use: 1) the output gap constructed with the CBO’s real potential GDP; 2) core PCE inflation; and 3) the short-term policy rate, $i_t$. The DSGE model uses the same data as Smets and Wouters (2007) but is updated and extended through 2019 and also uses $i_t$. The shadow federal funds rate comes from the work of Wu and Xia (2016) and is downloaded from Cynthia Wu’s website.\footnote{See https://sites.google.com/view/jingcynthiawu/shadow-rates?authuser=0}

1.4.1 Selection of Samples

The full data sample runs from 1960:Q1 to 2019:Q4. The starting period is consistent with the literature and constrained by availability of the PCE price index data. We truncate the sample in 2019 to exclude the new UMP that emerged during the COVID-19 pandemic and recession. The period during which the Fed targeted non-borrowed reserves (1979:Q4 to 1982:Q4) is included in the full sample rather than using arbitrary estimation methods to address missing observations.\footnote{Although the period of monetary targeting is volatile and influential in estimation, it is less so in the full sample than in the shorter subsamples.}

Based on the literature and conventional wisdom about known breaks in monetary policy, the subsamples are: I) 1960:Q1 to 1978:Q4; II) 1984:Q1 to 2007:Q2 (Great Moderation); and III) 2007:Q3 to 2019:Q4 (Global Financial Crisis, or GFC). The entire period 1979:Q1 to 1983:Q4 is omitted from subsamples I and II to avoid complications associated with policy changes to and from targeting of non-borrowed reserves, and because the exact dates of the estimated break points in the literature are heterogeneous (Table 1.1). Differences between econometric estimates from periods I and II are clearer this way, but the results are qualitatively similar (robust) to results when the non-borrowed reserve period is included in either period I or II (or in between). The beginning of sample III (2007:Q3) corresponds to the Fed’s initial rate cuts and early events of the financial
crisis, such as American Home Mortgage’s bankruptcy, BNP Parabas noting a decline in liquidity, the Dow Jones Industrial Average’s peak.

For robustness, we provide some formal evidence on the selected break points by estimating a split-sample Chow test for the VAR and testing for structural breaks (Lutkepohl, 2013). Figure 1.2 shows the p-value from the rolling window estimation; the horizontal dashed line indicates the 5 percent confidence level. The Chow test largely confirms our a priori reasoning on the subsample selection: structural breaks corresponding to the Fed’s changes in operating procedure in 1979Q3 and 1983Q1, as well as one near the start of the financial crisis in 2007Q3 (both indicated by the vertical dashed lines). For this reason, we continue the tradition in the literature of setting the break periods exogenously rather than using more complicated endogenous break-point methods. Additional potential breaks during the first subsample (I) are assumed not to be associated with monetary policy.

**Figure 1.2: Structural monetary shocks by model and sample**

![Results from Rolling Window Chow Test](image)

1.4.2 Estimation

The VAR is estimated using OLS so these Taylor Rule estimates are consistent with the recommendation of Carvahlo et al. (2021). The model has $k = 1$ lag for each sample for consistency and to conserve on degrees of freedom. The structural parameters are derived from $B_0$ and the first
own-lagged coefficient in the \( \hat{i}_t \) equation. Standard errors are obtained from the “delta” method (Oehlert, 1992).

The NK and DSGE models are estimated with standard Bayesian methods. Selection of priors has a significant bearing on the estimated parameters, so changing priors between subsamples can potentially bias results toward a structural break when one does not truly exist. To mitigate this bias, and for consistency with earlier research, we use the same prior distribution, mean, and standard deviation in the full sample and all subsamples: Canova’s (2009) for the NK model and Smets and Wouters’ (2007) for the DSGE model.\(^{15}\) The likelihood function is calculated using the Kalman filter. The posterior density distribution is obtained from the calculated likelihood function and prior distributions, continuing until convergence is achieved. Then the Metropolis-Hastings algorithm is used to create 2,000 draws of the posterior distribution and approximate moments of the distribution.\(^{16}\)

Following Smets and Wouters (2007), the DSGE output gap is generated from the model as the deviation from the level of output that would prevail with flexible wages and prices, \( y^p_t \). This model-generated output gap differs from the output gap used in the VAR and NK models in two ways. First, the latter uses CBO’s estimate of potential output derived from an independent growth-accounting framework.\(^{17}\) Second, because CBO estimates potential output for the full sample it does not change across subsamples; in contrast, the DSGE output gap is estimated separately for each subsample and thus is subject to breaks in the models’ structural parameters.

### 1.5 Estimation Results

This section reports coefficient estimates and evidence of structural breaks in model parameters. Tables 1.2 and 1.3 include Taylor Rule and other non-policy coefficient estimates, respectively, for

\(^{15}\)See Appendix A for a list of parameters, their roles in the model, and their priors.

\(^{16}\)Estimation is performed using a modified version of Johannes Pfeifer’s dynare code for Smets and Wouters’ model. Pfeifer’s code can be found at https://github.com/JohannesPfeifer/DSGE_mod/tree/master/Smets_Wouters_2007, and Dynare can be downloaded at https://dynare.org.

the full sample (Full) and each subsample (I-III). There are two subsample III periods depending on which funds rate is used: III\( _i \) (shadow funds rate) and III\( _i \) (fed funds rate). The tables also include coefficient changes between subsamples and, for the VAR model, significance of the t-tests for differences. As noted in Section 1.2, the break-test results for subsamples I and II are generally consistent with the prior literature, so this section focuses on comparing subsamples II and III. Coefficient magnitudes may vary across models due to differences in model variables and structure, and thus should be compared mainly across subsamples within models.

1.5.1 Taylor Rule Parameters

Table 1.2 reports estimates of the Taylor Rule parameters. During the Great Moderation, the estimated coefficients (column II) are broadly consistent with the prior literature.\(^{18}\) The Fed responds more to the inflation gap than output gap when setting interest rates i.e., \( \phi_\pi >> \phi_y \).\(^{19}\) The difference between these coefficients is largest in the DSGE model (1.97 versus .09). Interest rate persistence is similar across models but a bit lower in the NK model (approximately .6 versus .8). The DSGE model also shows a significant response to output growth (\( \phi_{\Delta y} \)).

\(^{18}\)Specifically, the Great Moderation point estimates for \( \phi_\pi \) are consistent with those estimated in Carvalho et al. (2022) via both OLS (2.75) and IV (2.63). While the subsample I estimates differ, their estimates have high standard errors.

\(^{19}\)Similarly, (\( \phi_\pi / \phi_y \)) is larger in subsample II than I
Table 1.2: Taylor Rule estimates by subsample and model

<table>
<thead>
<tr>
<th>Parameter Estimates</th>
<th>Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I-II</td>
</tr>
<tr>
<td>( \phi_\pi )</td>
<td>3.55</td>
</tr>
<tr>
<td></td>
<td>(1.61)</td>
</tr>
<tr>
<td>( \phi_y )</td>
<td>4.05</td>
</tr>
<tr>
<td></td>
<td>(.68)</td>
</tr>
<tr>
<td>( \rho )</td>
<td>.91</td>
</tr>
<tr>
<td></td>
<td>(.02)</td>
</tr>
<tr>
<td>( \phi_\pi )</td>
<td>1.37</td>
</tr>
<tr>
<td></td>
<td>[1.16,1.62]</td>
</tr>
<tr>
<td>( \phi_y )</td>
<td>.99</td>
</tr>
<tr>
<td></td>
<td>[.75,1.26]</td>
</tr>
<tr>
<td>( \rho )</td>
<td>.79</td>
</tr>
<tr>
<td>( \phi_\pi )</td>
<td>1.99</td>
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<tr>
<td></td>
<td>[1.57,2.41]</td>
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<tr>
<td>( \phi_y )</td>
<td>.30</td>
</tr>
<tr>
<td>( \rho )</td>
<td>.86</td>
</tr>
<tr>
<td>( \phi_{\Delta y} )</td>
<td>.41</td>
</tr>
</tbody>
</table>

Note: VAR estimates report the standard errors, and the NK and DSGE models report the 90% HPD confidence interval.

After the GFC, the estimated coefficients (column III) generally remained statistically significant but tended to revert back toward their period-I values (column I). In all three models, the Fed became less responsive to inflation as \( \phi_\pi \) declined by economically large and statistically significant amounts, although the VAR estimate (−1.61) is the wrong sign and not significantly different from zero. Changes in the other coefficients generally were smaller in absolute value and less systematic and significant. The response to output (\( \phi_y \)) increased (.12) significantly in the DSGE model but declined significantly in the VAR (−1.02) and insignificantly in the NK model (−.05). Persistence (\( \rho \)) increased significantly (.16) in the NK model but decreased significantly (−.09) in the DSGE model and was essentially unchanged in the VAR. The Fed’s response to output growth (\( \phi_{\Delta y} \)) also was essentially unchanged.
Table 1.2 also includes parameter estimates for the post-GFC period using the traditional effective federal funds rate (III\(i\)). Surprisingly, the fed funds coefficients are quite similar to those using the shadow rate (III\(\hat{i}\)). In fact, the coefficient magnitudes are essentially the same statistically with only a few key exceptions. In the VAR model, \(\phi_\pi\) is positive and much larger but still not significantly different from zero. In the NK model, \(\phi_y\) is only half as large (.31 versus .64). And in the DSGE model, the interest rate is economically more persistent (\(\rho = .92\) versus .75), presumably because the funds rate was constrained by the ELB from 2009-2015. The striking similarity between columns III\(\hat{i}\) and III\(i\) raises questions about the extent to which the shadow funds rate proxies for UMP.

1.5.2 Non-policy Parameters

Table 1.3 reports estimates of the models’ non-policy parameters. During the Great Moderation, these coefficients (column II) are generally, albeit roughly, consistent with the prior literature. In the NK model, the slope of the IS Curve (\(\psi\)) is negative and small in absolute value, implying a relatively high coefficient of relative risk aversion of about 50. The slope of the Phillips Curve (\(\kappa\)) and the expectations feedback are both positive and relatively high but significantly less than 1.0. The VAR and NK estimates of \(\kappa\) are very similar except during the Great Moderation (column II), where the NK slope is considerably more positive. The DSGE model has too many parameters to discuss individually, but the coefficient estimates are roughly in line with those reported in Smets and Wouters (2007) and subsequent estimates of their model. Unlike the Taylor Rule parameters, the NK and DSGE coefficients are not directly comparable due to substantial differences in the size and structural restrictions of the two models.
Table 1.3: Structural Estimates from New Keynesian and Bayesian DSGE Model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter Role</th>
<th>Full</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>I-II Change</th>
<th>II-III Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \kappa )</td>
<td>Phillips Curve</td>
<td>.01</td>
<td>.01</td>
<td>.02</td>
<td>.13</td>
<td>.02</td>
<td>.11***</td>
</tr>
<tr>
<td>( \psi )</td>
<td>IS Curve</td>
<td>-.02</td>
<td>-.07</td>
<td>-.03</td>
<td>-.19</td>
<td>.04</td>
<td>-.16</td>
</tr>
<tr>
<td>( \kappa )</td>
<td>Phillips Curve</td>
<td>.02</td>
<td>.02</td>
<td>.38</td>
<td>.03</td>
<td>.36</td>
<td>-.35</td>
</tr>
<tr>
<td>( \beta )</td>
<td>Inflation feedback</td>
<td>.70</td>
<td>.69</td>
<td>.91</td>
<td>.82</td>
<td>.22</td>
<td>-.09</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>Steady State Growth</td>
<td>-1.94</td>
<td>2.72</td>
<td>.79</td>
<td>-3.52</td>
<td>-1.93</td>
<td>-4.31</td>
</tr>
<tr>
<td>( \beta )</td>
<td>Steady State Hours</td>
<td>-1.94</td>
<td>2.72</td>
<td>.79</td>
<td>-3.52</td>
<td>-1.93</td>
<td>-4.31</td>
</tr>
<tr>
<td>( \rho )</td>
<td>Investment Adjustment</td>
<td>7.95</td>
<td>4.70</td>
<td>6.38</td>
<td>6.31</td>
<td>1.68</td>
<td>-.07</td>
</tr>
<tr>
<td>( \sigma_c )</td>
<td>Risk Aversion</td>
<td>1.53</td>
<td>1.64</td>
<td>1.25</td>
<td>.93</td>
<td>-.39</td>
<td>-.32</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>External Habit Degree</td>
<td>.74</td>
<td>.67</td>
<td>.52</td>
<td>.82</td>
<td>-.15</td>
<td>.30</td>
</tr>
<tr>
<td>( \zeta_w )</td>
<td>Calvo: Wages</td>
<td>.93</td>
<td>.75</td>
<td>.69</td>
<td>.73</td>
<td>-.06</td>
<td>.04</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>Frisch Elasticity</td>
<td>2.62</td>
<td>1.97</td>
<td>2.20</td>
<td>.97</td>
<td>.23</td>
<td>-1.23</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>Calvo: Prices</td>
<td>.83</td>
<td>.55</td>
<td>.81</td>
<td>.71</td>
<td>.26</td>
<td>-.10</td>
</tr>
<tr>
<td>( \sigma_w )</td>
<td>Wage Indexation</td>
<td>.72</td>
<td>.48</td>
<td>.46</td>
<td>.41</td>
<td>-.02</td>
<td>-.05</td>
</tr>
<tr>
<td>( \phi )</td>
<td>Price Indexation</td>
<td>.20</td>
<td>.37</td>
<td>.35</td>
<td>.33</td>
<td>-.02</td>
<td>-.02</td>
</tr>
<tr>
<td>( \psi )</td>
<td>Capacity Utilization Cost</td>
<td>.55</td>
<td>.28</td>
<td>.68</td>
<td>.71</td>
<td>.4</td>
<td>.03</td>
</tr>
<tr>
<td>( \Phi )</td>
<td>Fixed Cost Share</td>
<td>1.69</td>
<td>1.55</td>
<td>1.53</td>
<td>1.42</td>
<td>.02</td>
<td>-.13</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>Capital Share</td>
<td>.22</td>
<td>.24</td>
<td>.21</td>
<td>.12</td>
<td>-.03</td>
<td>-.09</td>
</tr>
<tr>
<td>( r^* )</td>
<td>Real Interest Rate</td>
<td>3.04</td>
<td>2.50</td>
<td>3.09</td>
<td>1.71</td>
<td>.59</td>
<td>-1.38</td>
</tr>
</tbody>
</table>

Note: VAR estimates report the standard errors, and the NK and DSGE models report the 90% HPD confidence interval.
After the GFC, many of the estimated non-policy coefficients (column III) in the NK and DSGE models exhibit significant changes. Unlike the Taylor Rule coefficients, however, there was not a general reversion back to period-I values but rather heterogeneous breaks in a variety of coefficients. In the NK model, the IS Curve slope ($\psi$) became more negative ($-0.19$ versus $-0.03$) and the coefficient of relative risk aversion fell to about 9 and the output gap is more sensitive to the real rate. The Phillips Curve slope ($\kappa$) declined considerably (0.38 to 0.03), returning to its approximate value before the Great Moderation. Inflation expectations ($\beta$) also decreased somewhat (0.91 to 0.82) but remained much closer to the rational benchmark (1.0) than before the Great Moderation.

In the DSGE model, several coefficients changed notably after the GFC. Two long-run coefficient, steady state growth ($\gamma$) and hours ($l$), fell by economically and statistically significant amounts (0.48 to 0.21 and 0.79 to $-3.52$, respectively). In contrast, steady state inflation ($\pi$) essentially was unchanged. The capital share ($\alpha$) declined by almost half and the external habit ($\lambda$) increased notably (0.51 to 0.83). The DSGE model also provides an estimates the natural real interest rate as a function of the rate of time preference, $\beta$, and risk aversion, $\sigma_c$.\textsuperscript{20} Estimates for periods I and II are larger than many in the literature but similar to the original estimates in Smets and Wouters (2007). In period III, the real rate estimates fell almost in half (3.1 to 1.7 percent). The remaining DSGE coefficients did not change statistically significantly.

1.5.3 Discussion

Evidence in this section suggests the presence of structural breaks in many coefficients. However, the analysis cannot verify econometrically whether the presence of UMP is responsible for the observed breaks without a clear alternative model that includes UMP, as discussed in Section 1.7.2. Nevertheless, it is instructive to summarize the results thus far and assess whether they provide suggestive evidence of changes in monetary policy. Three comparisons offer useful information and perspective:

\textsuperscript{20}The natural real interest rate is calculated as in Smets and Wouters (2007): $\bar{r} = \left(\frac{2^{\sigma_c\Pi}}{\beta} - 1\right)100$. 

21
• **Parameter types** – The structural breaks occur in both Taylor Rule (policy) and non-policy coefficients. This finding makes it even more difficult to isolate the effects of omitted policies on the Taylor Rule. Because the policy and non-policy parameters are estimated jointly, changes in the latter can influence estimates of the former.

• **Subsamples** – Structural breaks after the Financial Crisis (from II-III) are not always consistent with breaks during the Great Moderation (from I-II). For some parameters, breaks are statistically significant in only one period while for others it is significant in both (or neither). For some coefficients the breaks reverse sign from period II to period III, making the post-GFC coefficients similar to those before the Great Moderation, which is hard to explain.

• **Models** – Structural breaks are hard to compare between the parsimonious small models (VAR, NK) and the larger DSGE model. While none of the models includes UMP, the DSGE model has more variables that are likely to be influenced (directly or indirectly) by UMP. Thus, it is difficult to identify whether coefficient changes, especially non-policy, are due to omitted monetary policies or to changes in the private-sector economic structure.

Thus, the evidence presented thus far does not conclusively indicate whether UMP is responsible for the comprehensive and heterogeneous structural breaks in model parameters.

### 1.6 Additional Diagnostics

Motivated by the evidence thus far, this section examines additional diagnostic measures: 1) estimated structural shocks; 2) dynamic responses to structural shocks; and 3) estimated DSGE output gaps. These measures provide further evidence of structural breaks in period III and a fuller understanding of the economic nature of the observed changes.
1.6.1 Structural shocks

The time series characteristics of each model’s estimated structural shocks provide one way to summarize the comprehensive impact of parameter breaks. Figure 3 plots the estimated monetary policy shocks for each model from the full sample and each subsample.\(^{21}\) The correlation of monetary shocks between models varies from .83 to .91 the full sample. For the subsamples, the correlations vary from .54 (the VAR:NK correlation in period II) to .90 (the NK:DSGE correlation in period III.)

The full-sample monetary shocks for periods I and II are familiar and similar across models. The variance is greatest in period I, but even larger during the period of reserves targeting (1980-1983). The variance declined significantly during the Great Moderation due to “better monetary policy”, a phenomenon Stock and Watson (2002) and some others found to be the most influential cause of the Moderation. However, aside from some relatively modest fluctuations during the GFC recession, the full-sample monetary shock in period III did not exhibit another large change in variance (decrease or increase) following implementation of UMP.

\(^{21}\)See Figures 8 and 9 in the Appendix for plots of other structural shocks in the NK and DSGE models.
The relative variances of the monetary shocks in each subsample also are instructive. In period I, the subsample VAR and NK shocks are more volatile than the full-sample shock (ratios of 1.43 and 1.46, respectively), but the DSGE shock is much less variable (ratio of .35). While differences in shock variances across models are not surprising, the models exhibit heterogeneous changes in their shock variance ratios across subsamples as well. For the VAR and NK models, the monetary shock variance ratios in periods II and III (roughly .5 in both subsamples) are about one-third as large as in period I. In contrast, the DSGE monetary shock variance ratios in periods II and III (.13 and .39, respectively) are similar to period I. Thus, the DSGE monetary shock becomes

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22 See Table 4 in the Appendix for the full-sample standard deviations and the variance ratios for each subsample shock relative to its full-sample variance.
three times more variable in period III but there is not much change in the volatility of the VAR and NK shocks.

The autoregressive properties of the monetary shocks also vary not only across models but also across subsamples within the models. Persistence of the NK and DSGE monetary shocks generally increased in periods II and III, but the increase was statistically significant only in the DSGE model in period III (.31 to .54).

Changes in the time series properties of the estimated monetary shocks indirectly reflect the effects of changes in the estimated coefficients of Taylor Rule and non-policy structural equations reported in Section 5. While the estimated model coefficients exhibit various breaks, the time series properties of the monetary shocks in period III reveal moderate changes in variability and persistence. The changes are larger and more significant in the DSGE model (more variable and more persistent) perhaps because it contains more parameters and thus more opportunities to capture and interpret the breaks.

1.6.2 Impulse Responses

Changes in the Taylor Rule and non-policy parameters also affect the dynamic properties of the macro models. Figure 1.4 shows impulse responses to a 100-basis-point shock to the federal funds rate for the full sample and each subsample; recall that the post-GFC period (III) uses $\hat{i}_t$. These subsample impulse responses are unrestricted, allowing all policy and non-policy coefficients to change in each subsample.

The unrestricted responses are broadly consistent with prior evidence for each model and, with few exceptions, qualitatively similar across models and samples. Monetary tightening produces a familiar, modest decline in output and inflation, followed by a slow return to steady state for about 1-3 years. The funds rate paths are nearly the same, decaying slowly from 100 basis points in a similar fashion across models with only modest differences in the degree of persistence. This

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23 See Table 5 in the Appendix for complete set of autoregressive parameters for each model and sample.
24 The time series properties of the other estimated NK and DSGE structural shocks also exhibit a variety of changes but there are too many to discuss here. See the Appendix for more details and discussion of these other shocks.
result is consistent with the finding in Carvahlo et al (2021) that different estimation methods provide largely unbiased impulse response functions, although estimation methods may vary in precision.

However, the output gap and inflation responses exhibit somewhat larger and more economically important *quantitative* differences across models and subsamples. For example, although the average output response is similar across models and samples, the absolute magnitude of output responses varies more across samples in the VAR and NK models than the DSGE model. Also,
the DSGE has notably larger (in absolute value) and economically different inflation responses than the other models. In particular, the full sample responses are notably more muted for the NK model. Interestingly, no subsample response consistently matches the full-sample responses across models. A lack of consistency across models perhaps is to be expected given their different sizes and restrictions, but the relative inconsistency of subsample responses across models is striking. That is, the largest absolute response for each model is not associated with the same subsample.

Although subsample heterogeneity across responses may be providing additional evidence of structural breaks, most differences are economically moderate for at least two reasons. First, as noted in Section 1.6.1, the variances and persistence of the structural shocks change considerably across subsamples, which also impact the coefficient estimates. Unlike the monetary shock fixed at 100 basis points, impulse responses based on shocks’ estimated standard deviations (not displayed but available upon request) vary much more. Second, data-consistent dynamics are the inherent goal of model estimation. Thus, while breaks in the economic structure may occur in some coefficients (e.g., the Taylor Rule), offsetting breaks in other parameters (e.g., non-policy) may occur simultaneously to maintain dynamic properties consistent with the data.

To better understand the effects of structural breaks in Taylor Rule parameters, we conducted a counterfactual exercise in which the non-policy parameters are held fixed at their full-sample estimates. Figure 1.5 shows impulse responses to a 100-basis point fed funds shock using models in which only Taylor Rule coefficients change across subsamples, thus better illustrating the effects of structural breaks in policy on model dynamics.25

The counterfactual responses reveal three important insights. First, absolute magnitudes are roughly two to three times larger than the unrestricted responses (Figure 1.4) for all but the DSGE inflation response, which is about the same. Second, the counterfactual responses are much more consistent across subsamples with smaller qualitative differences. Third, the Great Moderation (period II) responses more consistently differ from the pre-Moderation (period I) and post-Crisis (period III) responses, which are similar to each other. The Great Moderation output and inflation

25Figures 1.5 and 1.6 exclude the VAR because its distinction between structure and reduced-form is less precise.
responses are smaller (more negative) in the NK model, and vice versa for the DSGE model. Except for the Great Moderation response, the NK fed funds rate responses exhibit a short-lived amplification after the shock while the DSGE responses do not. Overall, these counterfactual responses show that breaks in the non-policy parameters mute the volatility of responses differing only in Taylor Rules. Changes in Taylor Rule coefficients across samples and models thus have limited effects on model dynamics.

Figure 1.5: Counterfactual responses to a 100bp monetary shock by model and sample
For completeness, Figure 1.6 shows impulse responses to a 100-basis point fed funds shock for the converse counterfactual exercise. The Taylor Rule coefficients are held fixed at their full-sample estimates and only non-policy parameters change across subsamples, thus better illustrating the effects of changes in non-policy coefficients on model dynamics. The fixed-policy counterfactual responses of output and inflation also are larger (more negative) than the unrestricted responses, but not as much as when holding the non-policy coefficients fixed. Variation in non-policy coefficients holding the Taylor Rule fixed also produces more heterogeneous responses across subsamples, but the heterogeneity is not economically large.

Figure 1.6: Counterfactual responses to a 100bp monetary shock by model and sample
To summarize the dynamics results, changes in model coefficients have modest economic effects on dynamics when all coefficients are allowed change. Changes in subsets of the coefficients alter dynamic responses by magnitudes that are larger and economically more important, but these effects largely offset when all model coefficients are allowed to change.

### 1.6.3 Output Gaps

Figure 1.7 plots the DSGE output gaps for all samples along with the CBO output gap for comparison. Unlike the CBO output gap, changes in model coefficients across subsamples influence the estimated DSGE output gap and cause discontinuities across subsamples. The full-sample DSGE and CBO gaps are positively correlated and have comparable levels until about 1970. After that the DSGE gap diverges by many percentage points and becomes very persistent, rarely crossing zero. The magnitude of divergence is economically meaningful for monetary policy responses to output gaps in the Taylor Rule for all models. The divergence also may be a concern for construction and interpretation of the two gaps.\(^{26}\)

Figure 1.7 shows the DSGE output gap exhibits economically significant breaks across subsamples. The period-I and full-sample DSGE gaps are similar, and both are fairly close to the CBO gap. During the Great Moderation, however, the period-II DSGE gap is roughly 3-5 percentage points below the full-sample DSGE gap and crosses zero multiple times. After the GFC, the period-III and full-sample DSGE output gaps are about the same magnitude again and follow a similar U-shaped path. However, the period-III DSGE gap returns to zero faster and arrives there by 2020 like the CBO gap. In contrast, the full-sample DSGE gap is still around -4 percent. This discrepancy has major implications for the determination of optimal monetary (and fiscal) policy during the COVID-19 recession and recovery.

Subsample breaks in the DSGE output gap provide complementary evidence of structural breaks in the DSGE model coefficients. The results in Section 5 suggest that changes in long-

\(^{26}\)The original DSGE gap in Smets and Wouters (2007) was estimated through 2004 and corresponds more closely the CBO gap. See the Appendix for more details.
run coefficients like the steady-state growth rate likely play an important role, but changes in coefficients associated with wage-price block and Taylor Rule may also contribute. Alternatively, the results in this subsection may reflect the impact of the omission of explicit UMP in the macro model equations. Either way, failure to allow for structural breaks in model coefficients appears to lead to bias in the estimated full-sample DSGE output gap for long periods.

### 1.7 Explaining Structural Breaks

Existence of economically and statistically significant structural breaks in Taylor Rule and non-policy coefficients makes inference about cause(s) of the breaks much more difficult. If breaks occurred only in the Taylor Rule, it might be possible to discern shifts due to UMP. But with non-policy coefficients changing and the models omitting explicit specification of UMP, it is not feasible to identify breaks induced by UMP. Future research requires two extensions of the benchmark macro models. First, the models must incorporate time-variation in non-policy variables and
equations. Second, the models must explicitly specify UMP. This section suggests a road map for these complex tasks, which are beyond the scope of this paper.

### 1.7.1 Non-policy Time Variation

Several branches of the literature document and explain time variation in macroeconomic models. This subsection briefly summarizes selected topics and papers related to our results.

**Trend growth/productivity** – The DSGE steady state (trend) growth rate changed over time. One likely reason is trend breaks in productivity (total factor or labor), as documented in Fernald (2014), which may also lead to variation in the marginal product of capital. Endogenizing the processes of technical change and productivity growth may be productive.

**Natural real rate of interest** – The natural real interest rate \( r \) in equation 1.1 is a fixed the benchmark models, but Del Negro et al (2019) shows it varied widely over our full sample, rising then falling to its lowest level during period III; our real rate estimates show a similar decline.\(^{27}\) Time-variation in the natural rate might follow Laubach and Williams (2003). Their calculation of the natural real rate of interest, \( r^* = \frac{1}{\sigma} \tilde{\gamma} + \beta \), and its law of motion,

\[
r^*_t = c \tilde{\gamma}_t + z_t,
\]

would be added to the Taylor Rule, where steady state growth is allowed to vary over time (\( \tilde{\gamma}_t \)) while \( z_t \) captures other determinants of \( r^*_t \), such as household rate of time preference.

**Inflation target** – The benchmark models also assume the inflation target, \( \pi \), is fixed. However, inflation volatility during the Great Inflation and the subsequent steady decline (“opportunistic disinflation,” Orphanides and Wilcox 2002) suggest the target also may be time varying and merit inclusion in the benchmark models.

\(^{27}\) As noted earlier, our estimates of the natural real interest rate are consistent with Smets and Wouters (2007) original estimate of \( r^* \), it is considerably above the traditional estimate in the literature. Holston et al (2018) estimated the natural rate of interest to be close to zero after the financial crisis, and Del Negro et al (2019) estimate it to be slightly above one. Resolving these large inconsistencies around \( r^* \) is a key step to explaining structural breaks.
Policy maker preferences – The structural break in Taylor Rule coefficients during the Great Moderation (period II) has been described as a shift in the preferences of FOMC members toward favoring inflation stability.\textsuperscript{28} Bordo and Istrefi (2018) examine the Fed’s overall preference through the window of individual FOMC members tending to place a higher weight on the inflation gap (“Hawk”) or output gap (“Dove”) in setting the interest rate and find the FOMC shifted significantly toward being dominated by Doves after the GFC (period III). This observation is roughly consistent with the estimated Taylor Rules in period III, which generally show a small decline in $\phi_\pi$ relative to $\phi_y$.\textsuperscript{29} Time varying policy maker preferences could be modeled with $\phi_\pi$ and $\phi_y$ as functions of FOMC composition over time. Kocherlakota (2018) goes further arguing that policy makers have private information about their objectives (which may be influenced by non-economic factors) that only affects economic outcomes through the policy choice and thus acts like a taste shifter. If so, the unconditional independence of policy rules assumed in the benchmark macro models would be violated.

Phillips Curve and price stickiness – The slope of the NK Phillips Curve and the underlying degree of nominal price and wage stickiness changed, as noted in Kim et al. (2014) and Jorgenson and Lansing (2021), for examples. Trend developments such as improving information technology, declining influence of unions, and other factors may have influenced nominal stickiness and could be introduced to the models.

Rational expectations and monetary policy transparency – Estimated increases in coefficients on inflation expectations show growing importance of expectations. U.S. monetary policy also has embraced the anchoring of inflation to expectations, and has become more transparent and cooperative with the private sector (Spencer et al. 2013). Capturing these developments may require introducing time variation in the content and processing of information, learning, and other dynamics of expectation formation.

\textsuperscript{28}For examples, see Canova (2009), Castelnuovo (2012), Ilbas (2012), and Lakdawala (2016)
\textsuperscript{29}Debortoli and Nunes (2014) caution against interpreting structural shifts in the policy rule as simply a change in preferences, noting that shifts in the policy rule can obscure differences between factors inside and outside a policy maker’s control.
Heterogeneous preferences – Risk aversion in consumers declined. Given the challenges encountered in estimating this parameter (Calvet et al. 2021), it is hard to draw hard conclusions about the cause(s) of the estimated decline. Nevertheless, benchmark macro models may need to incorporate time variation in preference heterogeneity.

To summarize, the benchmark macro models may be exhibiting structural breaks in parameters that actually reflect some or all of these sources of time variation—and perhaps others not listed—rather than UMP. If so, allowing for more time variation in the models may either reduce evidence of structural breaks or more clearly identify the presence of breaks due to UMP. However, incorporating all or even some of these extensions and estimating the models is a challenging task that is beyond the scope of the current paper.

1.7.2 Unconventional Monetary Policies

During and after the GFC, the Federal Reserve implemented a wide range of UMP that can be classified into three broad categories: 1) forward guidance (FG); 2) quantitative easing (QE); and 3) expanded liquidity facilities (ELF).30 These new policies and tools are not in the benchmark macro models and thus may require modification of the Taylor Rule and/or addition of variables and structural equations (including new policy rules) to properly capture the effects of UMP.

Forward Guidance (FG) – Developed during the (relatively) low-interest rate period of the early 2000s, FG was tested first during the subsequent increase of the federal funds rate in 2004 (Gürkaynak, et al., 2004). The main implementation of FG occurred during the GFC when the federal funds rate hit the ELB for six years. Rather than using the shadow funds rate, it may be necessary to insert the prototypical FG model (equation 1.4) into the benchmark macro models. Richer specifications of the term structure and expectation formation also may be needed to identify the effects of UMP properly.

Quantitative Easing (QE) – From 2008-2014, the Fed substantially expanded its Open Market Operations (OMO) to conduct large-scale asset purchases (LSAP) of: 1) mortgage-backed secu-

30For more details of these policies, see https://www.federalreserve.gov/monetarypolicy/policytools.htm.
rities, to ease bank risk and lower mortgage rates; and 2) longer term Treasury bonds, to increase maturity and lower long-term risk-free rates. This QE strategy added two new dimensions to monetary policy. One is a simple balance sheet rule(s) like those proposed in Sims and Wu (2021), Sims et al (2021), and Dean (2021) that emulates the Taylor formula: 31

\[ B_t = \rho_B B_{t-1} + (1 - \rho_B)[\theta_\pi (\pi_t - \pi^*) + \theta_x x_t] + \nu_t \]  

(1.17)

where \( B_t \) is the Fed’s holding of long-term bonds. Dean (2021) also adds a term structure equation to the model. The other dimension is a de facto long-term target(s) and rule(s) for mortgage and/or Treasury bond rates. While Fed does not explicitly specify target long-term rates, the balance sheet rule implicitly suggests one. Most likely, macro models need to introduce explicit specifications of QE policies and asset-pricing equation(s) to identify the effects of UMP properly.32

**Expanded Liquidity Facilities (ELF)** – During and after the Financial Crisis, the Fed developed new policy tools to provide liquidity and improve functioning of financial markets. One type includes new short-term rates: 1) interest on excess reserves (IOER), which was replaced by interest on reserve balances (IORB) in 2021 after required reserves were eliminated; and 2) interest rates on overnight reverse repurchase agreements (ONRRP), a form of OMO. It is unclear whether more than one short-term rate is needed in the benchmark macro models, but it has been suggested that IORB should replace fed funds as the policy instrument.33 More research is needed to understand relationships among the short-term rates and the fed funds target range, especially how liquidity shortages emerge and cause financial instabilities that spill over into the real economy. Because IORB is the price that clears the market for bank (excess) reserves, it also is closely related to QE

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31 In practice, the FOMC appears to implement such a rule as changes in Fed’s target purchases of QE securities. See the November 22-23 FOMC statement for details.

32 Modeling UMP became even more challenging in 2020 with two new responses to the COVID-19 pandemic: 1) expanded QE that included purchases of investment-grade corporate bonds via the Secondary Market Corporate Credit Facility (SMCCF) and short-term state and local government notes via the Municipal Liquidity Facility (MLF); and 2) new direct lending to small and medium-sized businesses via the Paycheck Protection Program Liquidity Facility (PPPLF) and the Main Street Lending Program.

33 Former New York Fed President Bill Dudley argued recently the fed funds rate target (range) has become irrelevant so the Fed should drop it altogether and use the IOER (IORB) instead. See https://www.bloomberg.com/opinion/articles/2021-06-24/the-fed-s-interest-rate-target-is-obsolete
policies. A second type of new liquidity tool includes a variety of facilities that provide liquidity directly to banks, borrowers, and investors in key credit markets – some of which have expired.\textsuperscript{34} These other facilities are mainly relevant during liquidity crises and the Fed has demonstrated a willingness to start and stop facilities as needed. Introduction of such intermittent policy tools may also be needed in macro models but seems particularly challenging to specify.

To recap, observed structural breaks in the Taylor Rule may reflect the effects of omitting variables and equations associated with UMP. If so, expanding the macro models to incorporate the UMP and related non-policy equations may be necessary to fully and properly capture the effects of UMP. Recent research is developing theoretical foundations for some types of UMP.\textsuperscript{35} However, no theoretical model includes all elements of UMP, and there is little or no estimation of such models. Addressing these deficiencies is important for future research.

\subsection*{1.8 Conclusions}

Three classes of benchmark macroeconomic models exhibit economically and statistically significant breaks in their Taylor Rule and non-policy coefficients after 2007:Q3. Evidence of breaks is stronger and more widespread in the larger DSGE model. The main result pertaining to the Taylor rule is a decline in the strength of the Fed’s response to inflation relative to its response to output, making the Taylor Rule somewhat more similar to its form in the period before the Great Moderation. A structural break(s) was likely given the implementation of UMP that are not included explicitly in the benchmark models. However, it is unclear whether these widespread and heterogeneous breaks reflect the effects of UMP or something else. And, perhaps surprisingly, using a shadow rate to control for UMP and avoid the ELB does not alter the estimation outcomes much.

The observed structural breaks are heterogeneous and challenging to interpret well. One complicating factor is that breaks in non-policy coefficients influence the models as much or more.

\textsuperscript{34}See https://www.federalreserve.gov/monetarypolicy/policytools.htm  
\textsuperscript{35}Examples include Gertler and Karadi (2013), Hagedorn et al. (2019), and Sims and Wu (2021); Dean (2021) adds average inflation targeting (AIT).
than breaks in the Taylor Rule coefficients. Thus, many elements of the benchmark models may be susceptible to time variation that is not included in them. The first important task is to build and estimate a macro model(s) that incorporate some or all of the time-varying elements that are clouding inference about the effects of UMP. Then testing the revised model for structural breaks is more likely to identify the effects of UMP.

A second complicating factor is that the benchmark macro models do not include explicit specifications of UMP. Consequently, the observed structural breaks may be simply reflecting the estimation effects of omitted variables (and equations) rather than UMP. A form of the Lucas Critique (1978) also may be at work. After controlling for potential time-variation in macro models, the obvious remedy is to include explicit specifications of FG (augmented Taylor Rule or more), QE, and possibly ELP into the model(s). Testing for structural breaks in the revised model’s non-policy block of equations should more effectively identify the effects of the introduction of UMP.

Neither the task of controlling for time-variation in macro models nor the task of introducing explicit UMP instruments and rules is easy or fast. However, both are potentially important directions for future research and analysis of modern monetary policy.
Chapter 2

Better On Average? Average Inflation Targeting with Unconventional Monetary Policy

Figure 2.1: U.S. core Personal Consumption Expenditures inflation since 2015.

Note: The inflation projection is the median forecast from the Fed’s September 2021 Summary of Economic Projections.
2.1 Introduction

Since the 2008 Financial Crisis, monetary policy has faced a host of new challenges. The Federal Reserve lowered interest rates to their zero-lower bound in 2008, forcing it to utilize non-interest rate policies, such as quantitative easing, forward guidance, and targeted asset purchases. These “unconventional” policies allowed the Fed to influence economic outcomes when the interest rate is limited. While these were viewed as “break glass in case of emergency” policies, the economic shock associated with the recent COVID-19 pandemic forced the Fed to lower interest rates again to their lower bound and again utilize these policies. What’s more, the estimated decline in the natural rate of interest\(^1\) indicates unconventional policy will likely continue to be a piece of the monetary policy equation moving forward. Thus, these are now an important component of the Fed’s policy toolkit.

![Fed Funds Rate graph](image)

**Figure 2.2:** The fed funds rate since 2015.

**Note:** The Fed projection is the median forecast from the Fed’s September 2021 Summary of Economic Projections. The IT forecast uses a standard inflation targeting Taylor Rule while the AIT forecast uses a 5-year average inflation targeting Taylor Rule.

Meanwhile, inflation persistently undershot the Fed’s stated 2% goal from 2008-2020. (see Figure 2.1), and many began to view 2% as the Fed’s ceiling for inflation, rather than a symmetric target. These lowered inflation expectations push nominal interest rates down via the Fisher equation, increasing the frequency of the zero-lower bound and the need for unconventional policy.

\(^1\)See Laubach and Williams (2003) and Del Negro et al. (2017).
The Fed noted this challenge when reevaluating its policy framework, committing to an average inflation targeting (AIT) framework rather than targeting single period inflation. Instead of letting “bygones be bygones” regarding past undershooting, the Fed would now employ a makeup strategy, whereby past undershooting would be met with future overshooting. This, the Fed believed, would push inflation expectations closer to 2%, increasing nominal interest rates and decreasing the frequency with which unconventional policies are used. Since the economic reopening in late 2020, however, inflation has increased drastically to a 30-year high. Under the new framework, the Fed projects they will not begin raising rates until mid-2022, with rates settling at a lower long-run level (2.5%). Figure 2.2 compares the forecasted response of the fed funds rate under an inflation targeting Taylor Rule, a 5-year average inflation targeting Taylor Rule, and the median FOMC forecast. Under standard inflation targeting, the Taylor Rule would prescribe a tighter policy faster, while the 5-year AIT Taylor Rule prescribes a slower response and more closely matches the FOMC projections. This paper attempts to answer how this average inflation targeting will fare over time, and whether it leads to better outcomes than standard inflation targeting.

Research into average inflation targeting is largely just beginning. Nessen and Vestin (2005) are the first to consider how average inflation targeting can differ from traditional inflation targeting. They find a price level target strictly dominates both average inflation targeting and standard inflation targeting in a pure forward-looking model. However, when backward-looking elements are introduced, average inflation targeting can improve outcomes compared to both price level targeting and standard inflation targeting. Both Amano et al. (2020) and Budianto et al. (2020) extend this specification by incorporating the zero-lower bound into their analysis. Both find that average inflation targeting improves policy, even with a zero-lower bound, and the degree of history dependence is key to the policy’s effectiveness. Importantly, neither Amano et al. nor Budianto et al. consider the effect of unconventional monetary policy or financial frictions when evaluating average inflation targeting. Jia and Wu (2021) incorporate the time inconsistency of the policy, finding that AIT shifts the Phillips Curve and incentivizes the central bank to deviate from its stated policy. In turn, uncertainty can actually aid the central bank stabilize inflation and output. Mean-
while, empirical research has shown mixed effects of the introduction average inflation targeting. Coibion et al. (2020) showed that most of the public had not known about the shift in the Fed’s policy strategy, and Candia et al. (2021) found that, while many still had not known of the policy, their inflation expectations had begun to shift upwards.

In this paper, I evaluate the effectiveness of average inflation targeting in improving economic outcomes and decreasing the need for unconventional policy. I do this by incorporating imperfect information about average inflation targeting (AIT) into a DSGE model with an occasionally binding zero-lower bound and unconventional monetary policy. The model has an environment based on Sims and Wu (2021) and allows the central bank to set monetary policy using a simple interest rate rule, augmented for AIT, when interest rates are above the lower bound. However, when interest rates become constrained, the central bank can switch its policy instrument, using a policy rule for its balance sheet, similar to the Fed’s quantitative easing. Unconventional policy works by reducing financial frictions caused by the financial intermediary’s agency problem, allowing for greater firm investment and smoothed credit shocks. Additionally, average inflation targeting works as a trade-off between less stimulative policy contemporaneously and more stimulative policy in the future. Put simply, the effectiveness of average inflation targeting depends on its influence on expectations: if it can raise expectations enough to compensate for slower policy responses, it will be more effective than standard inflation targeting. However, under imperfect information, agents cannot directly observe the central bank’s averaging window. Instead, agents must form an expectation on the averaging window based on past policy, updating as more information becomes available.

Results show that average inflation targeting does, indeed, lead to a slower policy to shocks, so output and inflation decline more than the baseline case. However, these larger declines are met with greater increases in output and inflation in the future. Taken as a whole, simulations show that modest average inflation targeting can improve economic outcomes compared to the baseline under both full and imperfect information. These modest averaging windows more effectively stabilize inflation and decrease the zero-lower bound frequency, two of the Fed’s stated goals for
the framework. However, the central bank does run the risk of “over-averaging,” where they target average inflation over too long a period, leading to slower policy responses and greater instability. Overall, inflation is best stabilized by targeting inflation over 8 quarters under full information, while household welfare is maximized by targeting average inflation over longer periods. However, the success of the policy is dependant on the central bank’s ability to transparently commit to an averaging rule, as the most effective policy under imperfect information leads to consistently worse outcomes than the least effective policy under full information.

2.2 Additional Literature

This paper lies at the intersection of two strands of literature: that on unconventional monetary policies and alternative monetary policy goals. Several empirical papers have examined the effectiveness of non-interest rate policies, such as quantitative easing and forward guidance, in replacing traditional interest rate policies. An excellent summary of the literature surrounding unconventional policy can be found in Kuttner (2018). Papers such as Gagnon et al. (2011), Krishnamurthy and Vissing-Jorgensen (2011), and Baur and Neely (2014) take an event study approach to quantifying the effects of QE, finding that QE did significantly reduce long-term interest rates. Specifically, 10-year Treasury yields declined roughly 150 basis points in response to announcements of QE. Quantitative easing has also been shown to have effects on real outcomes as well. Rodnyansky and Darmouni (2017) and Luck and Zimmerman (2017) found that QE1 and QE3 led to increased bank lending, while Foley-Fischer, Ramcharan, and Yu (2016) found that firms issued more long-term debt in response to QE, leading to greater capital spending and employment. Finally, Engen, Laubach, and Reifschneider (2015) and Wu and Xia (2016) found that unconventional policies had similar effects on the overall economy to that of a 300 basis point decline in the fed funds rate.

Unconventional monetary policy has also presented new challenges for modelers. Indeed, the Fed’s use of non-interest rate instruments has necessitated modelers expand the sphere of policy and its transmission in macroeconomic models. Gertler and Karadi (2011, 2013), Carlstrom et
al. (2017) and Sims and Wu (2020, 2021) incorporate quantitative easing into a DSGE model by segmenting financial markets and incorporating financial frictions. These models allow quantitative easing to work slightly differently than traditional interest rate policy, as asset purchases ease financing constraints on firms and reduce the effect of financial frictions on banks. Other papers have begun to incorporate the idea that unconventional policy may have limited effectiveness as it is used more frequently. McMahon et al. (2018) find that inflation can become indeterminate when the central bank expends its balance sheet without restricting the composition of its assets, and Karadi and Nakov (2020) find QE loses its effectiveness to offset nonfinancial shocks as bank balance sheets become unconstrained.

While much has been made about the Fed’s shift to average inflation targeting, commitment and transparency are key determinants to the success of a shift in policy strategy. Erceg and Levin (2003) showed that the dynamics of inflation during the Volcker disinflation could largely be accounted for with rational, optimizing agents by incorporating imperfect information surrounding the inflation target. Ireland (2007) extends this imperfect information framework to estimate the Fed’s true inflation target from the 1950’s to early 2000’s, finding the target increased as high as 8% in the 1970s before settling at roughly 2.5% in the 2000s. Finally, De Michelis and Iacoviello (2016) examine the interaction of imperfect information and the zero-lower bound, applied to the introduction of Abenomics in Japan. They find information availability plays an even larger role in policy effectiveness when the interest rate is constrained by the zero-lower bound, as inflation and output are only half as responsive to changes in the inflation target under imperfect information.

### 2.3 Model

The model has an environment based on Sims and Wu (2021) containing both forward- and backward-looking elements with 6 types of agents: households, firms, financial intermediaries, the labor market, the fiscal authority, and the central bank. Households consume, hold short-term deposits, and a fraction of households supply labor through the labor union while the remainder are
intermediaries. The labor union purchases differentiated labor from the household and sells it as final labor to firms. There are 4 types of firms: retail, wholesale, capital producing, and final goods firms which transform capital and labor into final output. Wholesale firms must finance a portion of new projects by issuing long-term bonds. The financial intermediary can lend by holding these long-term bonds, but are subject to a value constraint. The fiscal authority finances its spending by levying lump-sum taxes on the household, collecting transfers from the central bank, and issuing long-term bonds. Finally, the central bank sets monetary policy according to two Taylor-type rules: one for interest rate policy when above the zero-lower bound, and one for bond-purchasing policy when against the zero-lower bound.

2.3.1 Households

There are two types of members within each household: workers and intermediaries. A fixed fraction of households are financial intermediaries, and each period intermediaries stochastically exit and become workers. Households all have the same lifetime utility function and maximize:

$$\mathbb{E}_t \sum_{j=0}^{\infty} \beta^j \left[ \ln (C_{t+j} - bC_{t+j-1}) - \frac{\xi L_{t+j}^{1+\eta}}{1+\eta} \right]$$  \hspace{1cm} (2.1)

where $\beta \in (0,1)$ is the discount factor, $b \in [0,1)$ is the habit formation parameter, $\eta$ is the inverse Frisch elasticity, $\xi$ is a scaling parameter, $C_t$ is consumption, and $L_t$ is the labor supplied. Households also face the following budget constraint when making their purchasing decisions:

$$P_tC_t + D_t - D_{t-1} \leq MRS_t L_t + DIV_t - P_t X - P_t T_t + (R_{t-1}^d - 1)D_{t-1}$$  \hspace{1cm} (2.2)

where $P_t$ is the price level, $D_{t-1}$ is the nominal level of deposits a household has entering period $t$, $R_{t-1}^d$ is the interest rate paid on those deposits, $MRS_t$ is the compensation a household receives for their labor supplied. $DIV_t$ are dividends received from ownership of nonfinancial firms, $X$ is startup capital for new intermediaries, and $T_t$ are lump-sum taxes.
2.3.2 Labor Market

The labor market consists of two portions: labor unions who purchase labor from households, and labor packers who sell final labor to firms. The labor union, indexed by $h \in [0, 1]$, is given by the demand curve:

$$L_{d,t}(h) = \left( \frac{W_t(h)}{W_t} \right)^{-\epsilon_w} L_{d,t}$$

(2.3)

where $W_t(h)$ is the wage paid for union $h$’s labor and $\epsilon_w$ is the elasticity of substitution. The aggregate wage is then simply:

$$W_t^{1-\epsilon_w} = \int_0^1 W_t(h)^{1-\epsilon_w} dh$$

(2.4)

Unions are subject to Calvo-style nominal wage rigidity, so each period unions face a $1 - \phi_w$ probability they can adjust their wage, with $\phi_w \in [0, 1]$. When wages are not updated, they can be indexed to inflation with the weight $\gamma_w \in [0, 1]$. Profit for a labor union is a function of the labor markup they receive by repackaging labor:

$$DIV_{L,t}(h) = W_t(h)^{1-\epsilon_w} W_t^{\epsilon_w} L_{d,t} - MRS_t W_t(h)^{\epsilon_w} W_t^{\epsilon_w} L_{d,t}$$

(2.5)

Labor unions, taking this into account, would optimally set the real wage, $w_t^* = \frac{W_t^*}{P_t}$, at:

$$w_t^* = \frac{\epsilon_w}{\epsilon_w - 1} \frac{f_{1,t}}{f_{2,t}}$$

(2.6)

$$f_{1,t} = mrs_t w_t^{\epsilon_w} L_{d,t} + \phi_w \mathbb{E}_t \Lambda_t \left( \frac{\Pi_t^{t+1}}{\Pi_t^{\epsilon_w}} \right)^{\epsilon_w} f_{1,t+1}$$

(2.7)

$$f_{2,t} = w_t^{\epsilon_w} L_{d,t} + \phi_w \mathbb{E}_t \Lambda_t \left( \frac{\Pi_t^{t+1}}{\Pi_t^{\epsilon_w}} \right)^{\epsilon_{w-1}} f_{2,t+1}$$

(2.8)
Integrating the union labor demand curve across $h$ gives the aggregate labor demand curve:

$$L_t = L_{d,t} v_t^w$$

(2.9)

where $v_t^w$ is the wage dispersion:

$$v_t^w = \int_0^1 \left( \frac{w_t(h)}{w_t} \right)^{-\epsilon_w} dh$$

(2.10)

which, combined with the optimal wage, $w^*$, gives the expression for the aggregate wage:

$$w_t^{1-\epsilon_w} = (1 - \phi_w)(w_t^*)^{1-\epsilon_w} + \phi_w \Gamma_{t-1} \epsilon_{w} \Pi_{t-1}^{\gamma_{w}(1-\epsilon_w)} w_{t-1}^{1-\epsilon_w}$$

(2.11)

### 2.3.3 Production Firms

There are four types of firms in the economy: wholesale, retail, capital producing, and final goods. Wholesale firms use capital and labor to create output, $Y_{m,t}$, capital producing firms create physical capital, $\hat{I}_t$, and retail firms repackage and sell wholesale output.

Retail firms face the demand curve:

$$Y_t(f) = \left( \frac{P_t(f)}{P_t} \right)^{\epsilon_p} Y_t$$

(2.12)

where $P_t(f)$ is the price of the retail output. The price of final output is then given by:

$$P_t^{1-\epsilon_p} = \int_0^1 P_t(f)^{1-\epsilon_p} df$$

(2.13)

where $\epsilon_p$ is the elasticity of substitution. Similar to labor unions, retailers face a Calvo-style price rigidity, so firms face a probability $1 - \phi_p$ of being able to adjust their price each period and
can index their price to inflation with weight $\gamma_p$. Taking this into account, firms maximize their dividends:

$$DIV_{R,t}(f) = P_t(f)^{1-\epsilon_p} P_t^{\epsilon_p} Y_t - P_{m,t} P_t(f)^{-\epsilon_p} P_t^{\epsilon_p} Y_t$$

(2.14)

Retailers attempt to optimally set prices at:

$$p_t^* = \frac{\epsilon_p}{\epsilon - 1} x_{1,t}$$

(2.15)

$$x_{1,t} = p_{m,t} Y_t + \phi_p \mathbb{E}_t \Lambda_t \left( \frac{\Pi_{t+1}}{\Pi_t^{\epsilon_p}} \right)^{\epsilon_p} x_{1,t+1}$$

(2.16)

$$x_{2,t} = Y_t + \phi_p \mathbb{E}_t \Lambda_t \left( \frac{\Pi_{t+1}}{\Pi_t^{\epsilon_p}} \right)^{\epsilon_p-1} x_{2,t+1}$$

(2.17)

Aggregating across all retail firms gives the aggregate price index:

$$1 = (1 - \phi_p) (p_t^*)^{1-\epsilon_p} + \phi_p \Pi_{t-1}^{(1-\epsilon_p)} \Pi_t^{\epsilon_p-1}$$

(2.18)

Wholesale firms produce output with a Cobb-Douglas production function:

$$Y_{m,t} = A_t (u_t K_t)^{\alpha} L_{d,t}^{1-\alpha}$$

(2.19)

where $Y_{m,t}$ is output, $L_{d,t}$ is the labor input, $\alpha$ is the capital share. $A_t$ is exogenous productivity which follows a stochastic process, $u_t$ is capital utilization, and the capital stock, $K_t$, accumulates with a normal law of motion:

$$K_{t+1} = \dot{K}_t + (1 - \delta(u_t)) K_t$$

(2.20)
Wholesale firms must finance a constant portion, $\psi \in [0, 1]$, of their new capital purchases, $\dot{I}_t$, bought at price $P^k_t$.\(^2\) To do this, similar to Carlstrom et al. (2017), firms must issue perpetual bonds. This creates the “loan in advance” constraint:

$$\psi P^k_t \dot{I}_t \leq Q_t CF_{m,t} = Q_t (F_{m,t} - \kappa F_{m,t-1}) \tag{2.21}$$

where $CF_{m,t}$ is the new nominal bond issuance, and $F_{m,t}$ is the total outstanding liability due in period $t$. These wholesale firms incorporate the loan in advance constraint and attempt to maximize dividends:

$$DIV_{m,t} = P_{m,t} A_t (u_t K_t)^\alpha L^{1-\alpha}_{d,t} - W_t L_{d,t} - P^k_t \dot{I}_t - F_{m,t-1} + Q_t (F_{m,t} - \kappa F_{m,t-1}) \tag{2.22}$$

Finally, capital producing firms produce new capital via:

$$\dot{I}_t = \left[1 - S \left( \frac{I_t}{I_{t-1}} \right) \right] I_t \tag{2.23}$$

from unused output, $I_t$, with the adjustment cost $S(\frac{I_t}{I_{t-1}})$. They maximize dividends given by:

$$DIV_{k,t} = P^k_t \left[1 - S \left( \frac{I_t}{I_{t-1}} \right) \right] I_t - P_t I_t \tag{2.24}$$

### 2.3.4 Long Term Bonds

Both the fiscal authority and wholesale firm can finance their endeavours by issuing long-term bonds. Similar to Woodford (2001), these bonds are modeled as perpetuities with a constant decaying coupon payment, where the decay parameter is given by $\kappa \in [0, 1]$. New nominal bond

\(^2\)While this fraction, $\psi$, is currently exogenous, future drafts of this paper will focus on endogenizing this so firms could attempt to take advantage of QE and good credit conditions
issuances for the government are given by \( CB_t \) and issuances for firms are given by \( CF_{m,t} \). Both follow a similar form where the total liability due in period \( t \) is based on previous issuances:

\[
B_t = CB_{t-1} + \kappa CB_{t-2} + \kappa^2 CB_{t-3} + \ldots \tag{2.25}
\]

Iterating forward gives:

\[
CB_t = B_t - \kappa B_{t-1} \tag{2.26}
\]

New government bond issuances are sold at the price \( Q_{B,t} \), while new corporate bond issuances sell at price \( Q_{F,t} \). Taken as a whole, the value of outstanding government and private bonds are given by

\[
Q_{B,t}B_t = Q_{B,t}CB_{t-1} + \kappa Q_{B,t}CB_{t-2} + \kappa^2 Q_{B,t}CB_{t-3} + \ldots \tag{2.27}
\]

\[
Q_{F,t}F_t = Q_{F,t}CF_{t-1} + \kappa Q_{F,t}CF_{t-2} + \kappa^2 Q_{F,t}CF_{t-3} + \ldots \tag{2.28}
\]

The interest rates on bonds, \( i_t^F \) and \( i_t^B \), are the realized holding period returns:

\[
i_t^B = \frac{1 + \kappa Q_{B,t}}{Q_{B,t-1}} \tag{2.29}
\]

\[
i_t^F = \frac{1 + \kappa Q_{F,t}}{Q_{F,t-1}} \tag{2.30}
\]

The term premium, modeled similar to Carlstrom et al. (2017), is the difference between the realized interest rate on government debt, \( i_t^B \), and the yield implied by the expectations hypothesis of the term structure as the sum of short rates over the life of the bond. The price and yield of the hypothetical expectations hypothesis bond are then:

\[
Q_{t}^{EH} = \mathbb{E}_t \frac{1 + \kappa}{i_{SS}^{t+1}} Q_{t+1}^{EH} \tag{2.31}
\]
\[ i_t^{EH} = \frac{1}{q_t^{EH}} + \kappa \]  

(2.32)

In turn, the term premium and risk premium are:

\[ tp_t = i_t^B - i_t^{EH} \]  

(2.33)

\[ rp_t = i_t^F - i_t^B \]  

(2.34)

### 2.3.5 Financial Intermediaries

Financial intermediaries in this model are based on those in Gertler and Karadi (2013). They finance their lending to firms and government, as well as their reserve holdings, by absorbing household savings. In doing so, intermediaries also engage in maturity transformation, holding short-term liabilities in the form of deposits while holding long-term assets in the form of government and corporate bonds. Each period, a fraction \( 1 - \sigma \), with \( \sigma \in [0, 1] \), of intermediaries stochastically exit, returning their net worth to households. These intermediaries are then replaced by new ones, beginning with the startup capital \( X \) from the household owner.

Intermediaries, indexed by \( z \), hold long-term bonds issued by both the government and wholesale firms, as well as interest-bearing reserves, \( RE_{z,t} \). They finance these holdings through their net worth, \( N_{z,t} \), and by issuing deposits, \( D_{z,t} \):

\[ Q_{F,t}F_{z,t} + Q_{B,t}B_{z,t} + RE_{z,t} = D_{z,t} + N_{z,t} \]  

(2.35)

Surviving intermediaries’ net worth is given by:

\[ N_{z,t} = (i_t^F - i_{t-1}^d)Q_{F,t-1}F_{z,t-1} + (i_t^B - i_{t-1}^d)Q_{B,t-1}B_{z,t-1} \]

\[ + (i_t^{RE} - i_{t-1}^d)RE_{z,t-1} + i_{t-1}^d N_{z,t-1} \]  

(2.36)
where $i_{t-1}^e$ is the interest rate on reserves, set by the central bank. $i_{t-1}^d$ is the equilibrium deposit rate, and interest rates in (2.36) are given by their net interest margin. Intermediaries attempt to maximize their terminal wealth, discounted by the stochastic discount factor, $\Lambda_t$:

$$V_{z,t} = \max(1 - \sigma) E_t \sum_{j=1}^{\infty} \sigma^{j-1} \Lambda_t n_{z,t+j}$$

with $n_{z,t} = N_{z,t}/P_t$. The financial intermediary faces two constraints. The first is a standard reserve requirement:

$$RE_{z,t} \geq \tau D_{z,t} \quad (2.37)$$

While the reserve requirement is an important piece in the intermediary’s maximization, it rarely binds, consistent with the Fed’s recent ample reserve regime.\(^3\) Second, intermediaries face a value constraint similar to that in Gertler and Karadi (2013). This constraint allows intermediaries to abscond with a portion of their assets at the end of a period instead of continuing as an intermediary. When an intermediary absconds, depositors can only recover a portion of the intermediary’s assets, while the intermediary retains the rest. Thus, for a depositor to lend to an intermediary, it must not be optimal for the intermediary to abscond and enter bankruptcy:

$$V_{z,t} \geq \theta_t (Q_{F,t} F_{z,t} + \Delta Q_{B,t} B_{z,t}) \quad (2.38)$$

Intuitively, the value constraint says that the value of continuing as an intermediary ($V_{z,t}$) must outweigh the value of the funds it can retain if it enters bankruptcy ($\theta_t [Q_{F,t} f_{z,t} + \Delta Q_{B,t} b_{z,t}]$). Once the intermediary enters bankruptcy, it keeps a fraction $\theta_t$ of its private bonds and $\theta_t \Delta$ of its government bonds, with $\Delta \in [0, 1]$. $\theta_t$ can thus be considered a credit wedge that arises from an agency problem in when an intermediary enters bankruptcy. Moreover, $\theta_t$ follows an AR(1) type process, and shocks can be considered a credit shock: when $\theta_t$ suddenly increases, depositors can

\(^3\)For a summary of how an ample reserve regime differs from a scarce reserve regime, see the explanation in Ihrig et al. (2020)
recover fewer assets, so the agency problem worsens. In turn, interest rate spreads must increase for intermediaries to be willing to continue.

Taken as a whole, intermediaries have the optimality conditions:

\[
E_t \Lambda_t \Omega_{t+1} \Pi_{t+1}^{-1} \left( i_{t+1}^B - i_t^d \right) = \frac{\lambda_t}{1 + \lambda_t} \theta_t \Delta \tag{2.39}
\]

\[
E_t \Lambda_t \Omega_{t+1} \Pi_{t+1}^{-1} \left( i_{t+1}^F - i_t^d \right) = \frac{\lambda_t}{1 + \lambda_t} \theta_t \tag{2.40}
\]

\[
E_t \Lambda_t \Omega_{t+1} \Pi_{t+1}^{-1} \left( i_{t+1}^{RE} - i_t^d \right) = -\frac{\omega_t}{1 + \lambda_t} \tag{2.41}
\]

where \( \lambda_t \geq 0 \) is the multiplier on the value constraint, \( \omega_t \) is the multiplier on the reserve requirement, and:

\[
\Omega_t = 1 - \sigma + \sigma (1 + \lambda_t) E_t \left[ \Lambda_{t+1} \Omega_{t+1} \Pi_{t+1}^{-1} \right] i_t^D - \frac{\sigma \omega_t R E_t}{N_t} \tag{2.42}
\]

When the value constraint (2.38) binds, an intermediary’s leverage ratio is given by:

\[
\phi_t = \frac{Q_{F,t} F_{z,t} + \Delta Q_{B,t} B_{z,t}}{N_{z,t}} \tag{2.43}
\]

This leverage ratio is lower than would be optimal for the intermediary, giving rise to excess returns on holding long-term bonds. However, when neither constraint binds (\( \lambda_t = \omega_t = 0 \)), the credit spreads decrease to zero (\( i_{t+1}^F = i_{t+1}^B = i_t^{RE} = i_t^D \)).

### 2.3.6 Monetary Policy

The central bank can conduct monetary policy via interest rate and balance-sheet policies while targeting average inflation. The central bank can hold both private and government bonds, and
it finances the purchases of these bonds by issuing interest-bearing reserves. The central bank balance sheet is given by:

\[ Q_{F,t}F_{cb,t} + Q_{B,t}B_{cb,t} = RE_t \] (2.44)

With standard policy, the central bank uses the short-term interest rate on reserves as its primary instrument to conduct policy, but the short-term interest rate can become constrained by the zero-lower bound. It sets policy according to a Taylor-type rule, responding to deviations of \( J \)-period average inflation from its stated inflation target, \( \bar{\pi} \), as well as to the growth rate in output\(^4\). The \( J \)-period average of inflation is denoted by \( \pi_t^J = \frac{1}{J} \sum_{j=0}^{J-1} \pi_{t-j} \). When the short-term interest rate is above the zero lower bound and the required reserve ratio is nonbinding, all short-term rates are equal to the desired policy rate:

\[ i_t = \max \{0, i_t^{TR} \} \] (2.45)

\[ i_t^{D} = i_t^{RE} = i_t^{TR} \] (2.46)

which is set according to:

\[ i_t^{TR} = \rho_{TR} i_{t-1}^{TR} + (1 - \rho_{TR}) \left[ \phi_\pi (\pi_t^J - \bar{\pi}) + \phi_Y (Y_t - Y_{t-1}) \right] + e_{i,t} \] (2.47)

where \( \rho_{TR} \) is the smoothing parameter, \( \phi_\pi \) is the inflation feedback parameter, and \( \phi_Y \) is the output growth feedback parameter. When the short-term interest rate becomes constrained by the zero-lower bound, the central bank then switches its policy instrument, utilizing its balance sheet in the

---

\(^4\)The Taylor Rule in this model responds to output growth, rather than the output gap, for two reasons: first, because of the presence of both nominal and financial frictions, it is not clear what “potential” output should be, as most models consider nominal frictions. Second, it is likely desirable for a central bank to focus on output growth, rather than an output gap, to resolve the imperfect knowledge problem discussed in Orphanides and Williams (2003).
spirit of the Fed’s quantitative easing programs. It adjusts its bond holdings according to a similar Taylor-type rules:

\[
F_{cb,t} = \rho_F F_{cb,t-1} + (1 - \rho_F) \Psi \left[ \phi_\pi (\pi_t^J - \bar{\pi}) + \phi_Y (Y_t - Y_{t-1}) \right] + e_{F,t} \tag{2.48}
\]

\[
B_{cb,t} = \rho_B B_{cb,t-1} + (1 - \rho_B) \Psi \left[ \phi_\pi (\pi_t^J - \bar{\pi}) + \phi_Y (Y_t - Y_{t-1}) \right] + e_{B,t} \tag{2.49}
\]

where \(\rho_B\) and \(\rho_F\) are the bond smoothing parameters and \(\Psi\) is a scaling parameter which maps the same inflation and output preferences to the bond-holding policy rule.

The central bank can purchase both government and corporate bonds, but corporate bond purchases have a greater effect for two reasons. First, the financial wedge allows intermediaries to abscond with more corporate bonds than government bonds, so corporate bond purchases ease this friction. Second, purchases of corporate bonds have a direct effect on the wholesale firm’s loan in advance constraint: first, the central bank buys bonds from banks, decreasing bank bond holdings \((F_t)\) and increasing reserves \((RE_t)\). These purchases increase the demand for outstanding corporate bonds, increasing bond prices \((Q_{F,t})\), decreasing the interest rate on bonds \((i^F_t)\) and excess returns \((i^F_t - i^{RE}_t)\). These higher bond prices, in turn, ease the loan in advance constraint, allowing for a greater level of investment with the same number of bonds outstanding.

**Policy Information**

As stated in the previous section, in this model the central bank targets \(J\)-period average inflation to reflect the Federal Reserve’s new operating framework. In September 2020, the Fed completed its review of its monetary policy framework, concluding that it would shift to targeting “flexible” average inflation, rather than its previous policy of single-period inflation. However, the Fed eschewed any mention of a specific averaging window, instead allowing for discretion in their new

---

5In the current specification of the model, the central bank can purchase both government and private securities. While this is standard for the ECB and BOJ, the Fed only began purchasing private securities under the CARES Act authorization. Thus, it is unclear whether this will become standard policy implementation going forward. Future drafts will consider how the model changes when the central bank can only buy government securities.
framework. In this model, I incorporate this uncertainty surrounding their averaging window similar to Erceg and Levin’s (2003) strategy of incorporating a time varying inflation target. In the case of full information, the central bank commits to a specific averaging window, which agents can directly observe. However, in the case of imperfect information, agents in the model know the parameters of the policy rule \((\rho_{TR}, \phi_{\pi}, \phi_{Y})\), but cannot directly observe the averaging window. In turn, they can only perceive innovations to the interest rate, \(Z_t\). These innovations could be the result of a standard monetary shock, \(e_t\), or a misperception of the averaging window, \(\pi^J\). Thus, the linear combination of these innovations is:

\[
Z_t = e_t - (1 - \rho_{TR})(\phi_{\pi})\pi^J_t
\]  
(2.50)

In turn, they must solve a signal extraction problem via the Kalman filter to form an expectation of the averaging window and the future path of interest rates based on policy innovations. In state space form, these components evolve according to the system:

\[
\begin{bmatrix}
\pi^J_t \\
e_t
\end{bmatrix} =
\begin{bmatrix}
\rho_{\pi^J} & 0 \\
0 & \rho_e
\end{bmatrix}
\begin{bmatrix}
\pi^J_{t-1} \\
e_{t-1}
\end{bmatrix} +
\begin{bmatrix}
\epsilon_{\pi^J,t} \\
\epsilon_{e,t}
\end{bmatrix}
\]  
(2.51)

where \(\epsilon_{\pi,t}\) and \(\epsilon_{e,t}\) are normal IID innovations with variances of \(\sigma_{\pi^J}^2, \sigma_e^2\), respectively. The averaging window has a high autoregressive root, while the monetary shock has an autoregressive root near zero. Intuitively, this means the central bank is committed to their unobserved policy rule, and they attempt to quickly correct for monetary shocks. The properties of these components are explored in depth in Erceg and Levin (2003), Ireland (2007), and De Michelis and Iacoviello (2016).

**Average Inflation Targeting**

In announcing the new framework, Fed Chair Jerome Powell noted that inflation had run persistently below its stated target of 2%, and that inflation expectations had become somewhat anchored.
at this lower level. Therefore, the goal of average inflation targeting is not just to makeup for the past undershooting of inflation, but also to reset inflation expectations closer to the Fed’s 2% target. This, in turn, should push interest rates higher, away from the zero-lower bound.

Expectations play a key role in the effectiveness of average inflation targeting. Regardless of the size of the averaging window, standard average inflation targeting works as a trade-off between less responsive policy contemporaneously and more responsive policy over time. Specifically, longer averaging windows raise household, firm, and intermediary inflation expectations, as they incorporate the central bank’s promise to “overshoot” in response to declines in inflation. These higher inflation expectations lead to comparatively higher wages and prices, higher long-term interest rates, and a greater overshoot in inflation and output over time. However, because policy is focused on longer-term goals and is less responsive to current shocks.

For example, a one percentage point decrease in current inflation causes the central bank to decrease rates by \((1 - \rho_{TR})\phi_{\pi \frac{1}{J}}\) percentage points under average inflation targeting, compared to \((1 - \rho_{TR})\phi_{\pi}\) percentage points under standard inflation targeting. As such, one would expect this slower contemporaneous movement to lead to greater short-term decreases in output and inflation from demand shocks, producing greater short-term declines in utility. However, policy is accommodative for longer under AIT, holding rates \((1 - \rho_{TR})\phi_{\pi \frac{1}{J}}\) percentage points lower for \(J\)–periods after the change in inflation\(^7\). In this way, average inflation targeting acts similar to forward guidance as a promise to hold rates lower for longer. Observing this future path of interest rates, households shift their expectations accordingly. Thus, intuitively, the effectiveness of average inflation targeting will depend on the relative effect of the shift in long-term expectations compared to the effect of smaller responses to current shocks. If re-set expectations play a larger role in determining the path of the economy, then AIT should improve policy-making compared to the baseline. However, if the dulled contemporaneous response of policy outweighs the effect of new expectations, standard inflation targeting should lead to better outcomes than average inflation.

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\(^6\) Coibion et al. (2020) and Naggart et al. (2021) discuss in greater detail how the announcement of AIT influenced inflation expectations.

\(^7\) Appendix 1 considers how the effectiveness of the policy changes if the central bank responds more strongly to current inflation by targeting decaying inflation, rather than an arithmetic average.
targeting. Moreover, the trade-off is likely to vary across averaging windows, as long averaging windows run the risk of over-averaging inflationary signals, leading to slow and suboptimal policy.

2.3.7 Government

The fiscal authority purchases an exogenous amount of final output, $G_t$, which is financed through lump-sum taxes, transfers from the central bank, and bond issuances, $B_{G,t}$. Because of financial frictions, Ricardian equivalence does not hold. However, lump sum taxes from the household adjust each period to ensure the government’s budget constraint holds. Thus, the government’s budget constraint is given by:

$$P_t G_t + P_{t-1} \bar{b}_G = P_t T_t + P_t T_{cb,t} + Q_{B,t} P_t \bar{b}_G (1 - \kappa \Pi_t^{-1})$$

(2.52)

2.3.8 Calibration

The model is solved using a piece-wise linear approximation around a non-stochastic steady state subject to the constraint that the interest rate never dip below the zero-lower bound. The model is solved using the OccBin toolbox developed in Guerrieri and Iacoviello (2015). Calibrated values of model parameters key to the analysis are described in Table 2.1. The values are standard to those in the literature. The bond decay parameter, $\kappa$, is calibrated so the average bond duration is 40 quarters; $\psi$, the proportion of new investment funded via debt, is taken to match the observed value of private debt to GDP. The intermediary survival probability, $\sigma$, is 0.95, in line with the value used in Gertler and Karadi (2011, 2013). The steady state risk spread, $i_t^F - i_t^B$, is calibrated at 200 basis points to match the average Baa - 10-year Treasury spread from 1970-2008, while the steady state term spread spread, $i_t^B - i_t^{EH}$, is calibrated at 100 basis points, the average 10-year Treasury - fed funds spread over the same period. The discount factor, $\beta$, is calibrated at a literature-standard 0.95, implying a natural real interest rate of 2%. The Calvo parameters, $\phi_p$ and $\phi_w$, and the indexation parameters, $\gamma_p$ and $\gamma_w$, are calibrated to their estimated value from Smets and Wouters (2007). Finally, the Taylor Rule parameters, $\phi_{\pi}$ and $\phi_Y$, are calibrated at their
standard value, and the Fed’s smoothing parameters, $\rho_{TR}, \rho_B$ and $\rho_F$, are calibrated so the Fed has consistent smoothing preferences between the fed funds rate and QE.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
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<tbody>
<tr>
<td>$\kappa$</td>
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<td>Bond duration</td>
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<tr>
<td>$\psi$</td>
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<td>Fraction of investment from debt</td>
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<td>$\sigma$</td>
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<td>Intermediary survival probability</td>
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<td>$\theta$</td>
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<td>$X$</td>
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<td>Steady state leverage</td>
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<tr>
<td>$\Delta$</td>
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<td>Government bond recoverability</td>
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<td>AR Fed bond holdings</td>
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<tr>
<td>$\beta$</td>
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<td>Discount factor</td>
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<td>$\phi_p, \phi_w$</td>
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<td>$\gamma_p, \gamma_w$</td>
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<td>Price/wage indexation</td>
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<tr>
<td>$\rho_{TR}$</td>
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<td>Taylor Rule: smoothing</td>
</tr>
<tr>
<td>$\phi_\pi$</td>
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<td>Taylor Rule: Inflation</td>
</tr>
<tr>
<td>$\phi_Y$</td>
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<td>Taylor Rule: Output growth</td>
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<td>$\rho_{\pi J}$</td>
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<td>AR: Average misperception</td>
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<tr>
<td>$\rho_e$</td>
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<td>AR: monetary shock</td>
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</table>

2.4 **Results: Full Information**

This paper examines the effectiveness of monetary policy changes along two dimensions: average inflation targeting and information availability. To isolate the effects of average inflation targeting vs standard inflation targeting, I first look at AIT only in the case of full information. Examining the policy through this lens shows the potential for average inflation targeting, provided the central bank transparently commits to a specific averaging window and households are attentive. Section 4.1 examines how the dynamics of the model vary with different averaging windows, while section 4.2 reports the results of a simulation where the model is hit by a variety of shocks.

2.4.1 **IRFs**

In addition to the standard inflation targeting baseline ($J = 1$), I consider 2 different averaging windows: $J = 8, J = 20$. Broadly, these averaging windows can be considered short and long
averaging windows. Impulse response functions from the model can be seen in Figures 2.3 - 2.6. Importantly, each model begins from its steady state, which has a real interest rate of 2%. Thus, each IRF begins with interest rate policy and only switches to QE if the zero-lower bound is reached. A consistent theme emerges across all IRFs: longer averaging windows lead to greater responses in each variable from the shock, and greater overshooting of each variable later in the IRF.

Figure 2.3 shows the response from a credit shock, or a sudden increase in \( \theta \). In response to the credit shock, output, employment, and inflation decline. This leads to a decline in household utility and causes the central bank to decrease its target interest rate to the lower bound. Interestingly, while output and employment decline more significantly with longer averaging windows, they recover more quickly. Moreover, the longer averaging windows lead to less time spent against the lower bound utilizing unconventional policies, returning interest rates to close to its steady state more quickly.

A productivity shock, shown in Figure 2.4, presents an interesting challenge for the central bank. Because output and inflation are moving in opposite directions, the weights in the Taylor Rule and the averaging window play an important role in the movement of the interest rate. Under standard inflation targeting, the central bank cuts rates modestly to counteract the decline in inflation. However, as longer averaging windows dull the sensitivity of the central bank to current inflation, the central bank actually raises rates modestly under AIT. The dynamics of other variables are largely similar in each scenario.

Figure 2.5 shows the response of the model to 100bp interest rate shock. Interestingly, output and employment decline more after a 100bp interest rate shock under AIT than they do under standard IT, while the inflation response is similar. These greater declines are likely due to slower expected policy responses in the future, as the central bank is responding to average inflation rather than the large decline in current inflation.

Finally, while output and employment respond similarly to a government spending shock, inflation increases significantly more with longer averaging windows. This, in turn, requires the
central bank to undershoot inflation more in later periods to stabilize average inflation, leading to lower interest rates and a similar level of output.

### 2.4.2 Simulation Results

Next, I simulate the model across 1,000 periods to see how average inflation targeting compares to standard inflation targeting when the economy is hit by a combination of shocks, rather than each in shock isolation. Each variable begins in steady state, and is hit with a sequence of credit, technology, interest rate, and productivity shocks.

Variances of output, inflation, the interest rate, and utility from the full information simulation can be seen as the black lines in Figure 2.7. A notable takeaway from the table is that variables are stabilized best with different averaging windows. Output is best stabilized using standard inflation targeting, and becomes less stable as the averaging window increases. Alternatively, inflation is most stable with a moderate averaging window ($J = 8$ quarters) and least stable under the baseline, $J = 1$. Interest rates are most stable with a longer averaging window. This is largely expected, as longer averaging windows will slow the policy response to inflation. Finally, utility is best stabilized under standard inflation targeting, largely because output is more stable. Thus, while AIT can clearly stabilize inflation more effectively, it is not a free lunch.

A rationale behind the average inflation targeting was to push interest rates away from the zero lower bound, decreasing the use of unconventional policies. Interestingly, this rationale looks to hold true, at least for moderate averaging windows. Policy hits the zero-lower bound in 9.3% of the simulation when inflation is targeted over $J = 8$ quarters, and only 8% when targeted of $J = 12$ quarters. In contrast, the baseline hits the zero-lower bound in over 9% of periods the simulation, so standard policy is more likely to have to resort to unconventional policies, like QE, than moderate average inflation targeting. However, there is a risk in over-averaging inflationary signals through this lens too, as a long averaging window of $J = 20$ quarters hits the zero-lower bound in 10% of the simulation.
Figure 2.3: Response to a credit shock

Figure 2.4: Response to a productivity shock
Figure 2.5: Response to an interest rate shock

Figure 2.6: Response to a government spending shock
Figure 2.7: Variance of variables from simulation.

Note: Model is simulated over 1,000 periods with random shocks to credit, productivity, spending, and the interest rate.

Figure 2.8: Total utility and ZLB frequency from simulations.

Note: Model is simulated over 1,000 periods with random shocks to credit, productivity, spending, and the interest rate.
2.5 Results: Imperfect Information

Figure 2.9: Response from the first 50 periods of the simulation
Each variable under full and imperfect information with a \( J = 8 \) period averaging window

While targeting average inflation over moderate periods can lower the variability of inflation and increase total household utility, these results assume households and firms have perfect information about the averaging window, and that the central bank will commit to the averaging. However, the Fed has not publicly stated how they plan to implement the new policy framework. What’s more, surveys done by Coibion and Gorodnichenko (2020) and Candia et al. (2021) show that most households did not know about the policy shift, and inflation expectations had become “unanchored” and began to drift upwards. In turn, there has been a substantial amount of uncertainty about how high inflation will get, and how soon and forcefully the Fed will respond. Clearly, there is imperfect information surrounding average inflation targeting, due to both ambiguity by the Fed on the policy roll-out and by household and firm inattention.

Figure 2.9 shows plots of each variable over the first 100 periods of the simulation, holding the averaging window constant at \( J = 8 \) periods. Holding the averaging window constant iso-
lates the effect of imperfect information surrounding average inflation targeting. Importantly, each variable appears to be less stable under imperfect information, as output and employment quickly increase more above their steady state, leading to higher inflation. Inflation stays at a higher level for longer under imperfect information, as there is uncertainty surrounding the perceived averaging window. Interest rates hit the zero-lower bound early in the simulation for both full and imperfect information, but they remain against the zero-lower bound for longer under imperfect information. What’s more, interest rates are driven to the lower bound a second time under imperfect information. Taken as a whole, the full information policy leads to a smaller central bank balance sheet over the simulation, as unconventional policies are both more effective and used less frequently.

The blue lines in Figures 2.7 and 2.8 show how the variance of inflation, output, and the interest rate change under imperfect information. Interestingly, output is most stable under a standard inflation targeting regime, similar to the full information policy. Moreover, inflation is most stable over a shorter averaging window (roughly 8 quarters), and has roughly equivalent variance under standard inflation targeting and long averaging windows. Interest rates are most stable under longer averaging windows, though the variance is roughly stable between a moderate AIT and a long AIT.

Utility is most stable under standard inflation targeting or short AIT, largely due to greater stability in output with shorter averaging windows. However, while under full information utility is similarly high under short and long averaging windows, utility is highest under a short averaging window with imperfect information. This reveals the tradeoff that AIT faces under imperfect information. Targeting inflation over longer averaging windows dulls the effect of imperfect information in a single period. However, longer averaging windows lead to slower contemporaneous responses and the higher variance of output seen in Figure 2.7. This trade-off is most effectively balanced when inflation is targeted over 4 quarters, and there are similar effects between moderate and long windows.

Finally, interest rates hit the zero-lower bound less frequently under long averaging, and the frequency increases as the averaging window shortens. Thus, under imperfect information, the central bank balance sheet stays smaller when policy targets inflation over longer windows.
Importantly, the performance of the model under imperfect information is strictly dominated by full information: the variance of each variable is lower, total utility is higher, and the zero-lower bound tends to bind less frequently. This illustrates the importance of information for a policy’s effectiveness: when agents don’t know the specifics around AIT, they frequently must update not only their expectations about the future, but also their expectations about the true policy rule. This additional uncertainty makes it more difficult for households to plan consumption and firms to plan investment decisions, leading to greater variances and lower total welfare. In short, AIT has benefits over standard inflation targeting if the central bank credibly commits to a specific rule and the households are attentive. However, if the central bank cannot commit, or households simply are inattentive to a policy change, the model shows outcomes are better if the Fed returns to a commitment to standard inflation targeting.

2.6 Conclusion & Policy Implications

In this paper, I evaluate the effectiveness of average inflation targeting in the context of a DSGE model with an occasionally binding zero-lower bound, unconventional monetary policy, and imperfect information about the policy. This is an important step in the literature around average inflation targeting, as previous papers have only considered AIT in the context of interest rate policy and had not fully incorporated policy information availability. I emphasize that targeting average inflation plays an important role in the formation of expectations, and the effectiveness of the policy depends on its ability to influence expectations. Overall, average inflation targeting more effectively stabilizes inflation compared to the standard inflation targeting baseline. Moreover, it decreases the incidence of the zero lower bound, and improves the effectiveness of unconventional policies.

Taken as a whole, the combination of inflation and output are most effectively stabilized when the central bank targets inflation over a period of 1-2 years under both perfect and imperfect infor-
This modest averaging window also decreases the frequency with which interest rates hit the zero-lower bound and the central bank shifts to unconventional policy.

However, average inflation targeting is not without its own drawbacks. Inflation increases much more substantially in response to positive demand shocks under AIT, requiring the central bank to undershoot inflation in the future. Additionally, targeting inflation over long periods can mitigate the benefits of AIT, slowing monetary policy’s response to current shocks and leading to greater instability. This, in turn, means interest rates actually hit the zero-lower bound more frequently when targeting average inflation for periods longer than 3 years. Moreover, switching policy frameworks introduces uncertainty, as shown by Coibion and Gorodnichenko (2020) and Candia et al (2021). Under imperfect information, households and firms have a harder time forming expectations, leading to lower overall welfare. Thus, credibility and transparency of the averaging window is key to the effectiveness of the policy. In short, AIT has benefits if the central bank credibly and transparently commits to the policy, and households pay attention to the policy shift. However, AIT can create new uncertainty that outweighs the potential benefits.

There is a promising research frontier based on these results, as future research can focus on how the effectiveness of AIT changes when households have a more direct involvement in the financial sector, through either holding mortgages or long-term bonds. Additionally, research can focus on incorporating default risk into the structure of interest rates, allowing for a more formal modeling of both the term and risk structure. Finally, future research can take a more empirical approach, examining how sustainably interest rates and inflation stabilize at a higher level as the effects of the COVID-19 pandemic wane and the economy begins to return to a more normal state.
Chapter 3

Interest Bearing Reserves and Monetary Policy Implementation

3.1 Introduction

Prior to 2008, the Federal Reserve mainly conducted policy by affecting the quantity of reserves in the banking system to move the fed funds rate. If they wanted to raise the interest rate, they would simply decrease the quantity of reserves through open market operations, increasing the interest rate. To lower the interest rate, they would increase the quantity of reserves. However, quantitative easing drastically increased the number of reserves in the financial system, leaving the Fed unwilling to reduce the number of reserves to conduct policy in this pre-2008 manor. Instead, the Fed now conducts policy through manipulating a new policy: interest on reserves (IOR). The idea of interest on reserves goes back to at least Lauchlin Currie’s proposed 1935 banking reforms in response to the Great Depression (Phillips & Minsky, 1996). Milton Friedman (1960) even theorized that paying interest on reserves (IOR) would centralize more of the money supply at the central bank, giving it greater influence over the money supply and short term interest rates because banks demand a higher quantity of reserves.
However, it took until 2006 for Congress to authorize the Fed to ability to pay interest on reserves. The law intended to incentivize banks to hold reserves beyond what was required. The policy was originally slated to go into effect in 2011, but the Fed moved the start date up to October 2008, hoping to gain an additional policy tool and to increase bank reserve holdings in response to the financial crisis. The Bank of England started paying interest on reserves shortly thereafter in 2009, while the European Central Bank had since its inception in 1999. Shortly after the policy was implemented, the amount of reserves in the system increased significantly and has continued to stay high since (Figure 1) due to a greater incentive to hold reserves, a desire by banks to hold more reserves in response to the financial crisis, and quantitative easing.

The Fed’s use of interest on reserves as standard policy worldwide is merely 15 years old, and the literature behind it is just now beginning to blossom. Further, there is still much debate on the proper way to model interest on reserves, and some ambiguity around the effects of the policy on both the fed funds market and the economy as a whole. Some of this ambiguity lies in the uncertainty around the proper model to use. The literature thus far has largely focused on the Federal Reserve but has somewhat ignored the bank side of the market and, to a certain extent, financial markets. A focus on how banks allocate assets when interest is paid on reserves can give insight into how IOR changed the Fed’s instruments. The structure of this paper is as follows: section II examines the theoretical benefits of the policy, section III discusses why these theories did not hold and builds a model of the fed funds market with IOR, section IV looks at the implementation of monetary policy with IOR, and section V concludes.

### 3.2 Early Theories

Paying interest on reserves theoretically gives a central bank a greater amount of control over the economy by putting a floor on the overnight rate (Figure 3.2) and allowing policymakers to better dictate inflation expectations. The primary rationale for paying interest on reserves was put forth by Goodfriend (2002). Goodfriend discusses how innovations in payment methods began to worry
economists that central banks could lose some control over interest rates in the future. Competition among currencies, especially with the introduction of cryptocurrency, lessens a central bank’s power over the market by shrinking the relative size of their instruments. Put another way: if fewer people transact in dollars, people are less sensitive to the interest rate on dollars. Additionally, the 1990’s in Japan showed that deflation could occur at the zero lower bound. Central banks needed to further consider what can or should be done in this case, and whether they have the correct tools to implement an appropriate policy.

Goodfriend lays out how a central bank can implement interest on reserves by first satiating the market for reserves. A satiated market for reserves will drive the interest rate to its lower bound because there will already exist supply to satisfy changes in demand. In tandem, the central bank can institute interest on reserves. This can act as a floor for the overnight market for reserves: banks will not lend below the IOR rate because they can simply hold their excess reserves and earn interest. As a result, a central bank would be free to use open market operations to pursue short-run financial stability, changing the quantity of reserves to ensure banks are adequately capitalized. A central bank can move the interest rate in the overnight market for reserves by simply adjusting the IOR rate, then adjusting bank reserves to smooth shocks to the financial system. The policy would also aid a bank’s risk profile by allowing it to shift from other, riskier interest bearing assets to a
perfectly safe interest bearing asset of reserves. This allows a central bank to limit how much of its own capital is used for investment in private credit by banks. In short, Goodfriend (2002) sees paying interest on reserves as an effective way to combat changes in the structure around monetary policy without compromising the effectiveness of policy in the short run.

Kashyap and Stein (2012) look at additional theoretical benefits of IOR. They begin with the assumption that the Fed can set IOR and the fed funds rate separately and explore how the central bank can use IOR to combat externalities created by bank debt. In their model, banks can change their maturity positions at the start of each period. As a bank sells off its shorter term assets in favor of long term assets, it depresses the price of short term assets. This tightens constraints on other institutions in the market, forcing them to change their maturity position as well to reflect the new asset values. In turn, banks create an externality by changing their maturity position. Kashyap and Stein use their model with a representative bank to explore how monetary policy can implement a sort of Pigouvian tax or cap and trade regulation to curb the effect of these externalities. These pseudo-regulatory policies can be implemented through changes in the reserve...
requirement and changes in the scarcity of reserves. However, for a central bank to implement this through controlling the scarcity of reserves, it cannot have an excessively large balance sheet as described by Goodfriend (2002). The introduction of interest on reserves gives a central bank an additional tool, allowing it to use the interest rate on reserves to change a bank’s optimal maturity position and change the quantity of reserves to influence financial market liquidity. In this system, a central bank can control financial stability through its management of the total quantity of reserves and reserve requirements, thereby forcing the market to internalize its externality. Additionally, a central bank can control inflation through its manipulation of the interest rate on reserves.

Berentsen and Monnet (2008) explore how similar staggered funding decisions occur through a channel system in which the central banks sets upper and lower bounds for its target rate and allows the market to equilibrate in that range. They define the policy rate to be the average of the rate on reserves and the discount rate, \( r^f = \frac{r_d + r_{ior}}{2} \) and assume the discount rate is always greater than or equal to the interest rate on reserves \( r_d \geq r_{ior} \). Through the Fisher equation, they find inflation increases as the policy interest rate increases. Perhaps most importantly, policy can be tightened by simply increasing the size of the spread. When the spread increases, there is less relative liquidity in the financial system, increasing interest rates across the board and decreasing consumption. As a result, Berentsen and Monnet point out that optimal policy in an interest on reserves world must focus on the interest rate corridor, that is it must specify both the upper and lower bounds of policy.

### 3.3 Realities of the Policy

While many of these earlier papers theorized that the Fed could set IOR and the fed funds rate independently, or that IOR would put a floor on the fed funds rate, data quickly showed neither of these predictions would hold. As Figure 3.3 shows, the fed funds rate has been consistently below the IOR rate. Transcripts from the Federal Reserve’s October and December 2008 meetings showed many Fed officials struggling to understand this phenomenon. This confusion culminated
in the December meeting with then-San Francisco Fed President Janet Yellen admitting “interest on reserves isn’t working quite the way we expected,” and then-Governor Elizabeth Duke noting that “this experience with interest on reserves is brand new for us, and I don’t think we’ve had enough experience to know how it is actually going to work.” Furthermore, the strong and consistent comovement between IOR and fed funds indicates that the two are not set independently, but are instead a part of the same monetary policy stance. This, in turn, left the literature with two key questions: first, why does IOR not act as a floor on fed funds, as Goodfriend (2002) had predicted? And second, given the two rates are not set independently, how can monetary policy be conducted?

Many of these papers start with a framework of a model of the interaction between the central bank and banks, similar to the one used in Armenter and Lester (2016). In the model, there are 3 primary agents: nondepository institutions without access to IOR (such as government sponsored entities like Fannie Mae and Freddie Mac), depository institutions (such as banks) with access to IOR, and the Fed. The Fed directly controls two policies: the interest rate on reserves, $r_{ior}$ and the interest rate in a reverse repurchase facility (ON RRP), $r_{rrp}$, where the IOR rate is always set above the ON RRP rate ($r_{ior} >> r_{rrp}$). In turn, the fed funds rate, $r_{ff}$, is determined in equilibrium. A visual representation of the market can be seen in figure 3.4, and the timing of decisions of the market in figure 3.5.
Lenders are nondepository institutions who cannot deposit their reserves at the central bank, but they can loan through the fed funds market to a depository institution who can deposit it at the central bank and earn the interest on reserve rate, $r^{\text{OFI}}$. Each depository institution, $j$, can hold these deposits at the central bank and will then keep a portion of the return as its own profit for the transaction. However, it is possible that not all lenders match with depository institutions, so lenders who do not match can enter the overnight reverse repurchase (ON RRP) facility and earn $r^{\text{RRP}}$. A depository institution bears a balance sheet cost, $c_j$, which increases if it holds reserves for lenders. Lastly, if a depository institution offers a lower interest rate in the fed funds market, they have a lower probability of matching because lenders will attempt to match with another depository.
institutions. However, if a depository institution offers a higher interest rate, they have a higher probability of matching, but have to pay forward more of the interest on reserves rate. As a result, lenders maximize their profit using the fed funds market rate, \( r^{ff} \):

\[
\pi(r^{ff}, q_j) = \left[ \frac{1 - e^{-q_j}}{q_j} \right] r^{ff} + \left[ 1 - \frac{1 - e^{-q_j}}{q_j} \right] r^{rrp} \tag{3.1}
\]

\[
\pi(r^{ff}, q_j) = \Pi \tag{3.2}
\]

\( \frac{1-e^{-q_j}}{q_j} \) in equation (3.1) is the probability that the lender is matched with a depository institution, where \( q_j \) is the ratio of lenders to depository institutions. A depository institution’s choice to enter the fed funds market depends on their balance sheet cost, \( c_j \). A matched firm receives the fed funds rate, \( r^{ff} \). The second term \( (1 - \frac{1-e^{-q_j}}{q_j}) \) is the probability the lender is not matched and enters the ON RRP facility. Equation (3.2) says that for a depository institution to attract lenders, their expected payoff must be equal to market profit. Solving (3.1) and (3.2) gives for the fed funds rate gives:

\[
r^{ff} = r^{rrp} + \left[ \frac{q_j}{1 - e^{-q_j}} \right] (\Pi - r^{rrp}) \tag{3.3}
\]

Depository institutions with balance sheet cost \( c_j \) who choose to enter the fed funds market solve:

\[
\max_{r^{ff}, q_j} [1 - e^{-q_j}](r^{ior} - c_j - r^{ff}) \tag{3.4}
\]

Subject to equation 3. Solving equation 4 gives the optimal fed funds rate and market tightness:

\[
r^{ff} = r^{rrp} + \log \left( \frac{r^{ior} - c_j - r^{rrp}}{\Pi - r^{rrp}} \right) \left[ \frac{(r^{ior} - c_j - r^{rrp})(\Pi - r^{rrp})}{(r^{ior} - c_j - \Pi)} \right] \tag{3.5}
\]

\[
q_j = \log \left( \frac{r^{ior} - c_j - r^{rrp}}{\Pi - r^{rrp}} \right) \tag{3.6}
\]
Bech and Klee (2009) point to two primary factors to explain why IOR does not serve as a floor for fed funds: first, not all firms who participate in the fed funds market are eligible to receive interest on reserves. Many nondepository institutions, such as “shadow banks” and government sponsored entities, rely on the overnight market for their day-to-day funding and cannot receive interest on reserves or do not hold reserves. Next, many banks are able to borrow funds from these nondepository institutions and hold them at the Federal Reserve to collect interest on them, allowing for arbitrage in the banking market. In turn, many government sponsored entities have tightened their credit lines. Bech and Klee incorporate banks’ and nonbanks’ market power into a model similar to that above by weighting the probability of matching in equations (3.1) and (4) by the bargaining power of the firm. In essence, banks who do not need to borrow reserves to meet regulatory or withdrawal obligations have greater bargaining power in the fed funds market. These banks can instead use fed funds loans from nonbanks solely as a way to arbitrage IOR. Their model shows that there will exist a spread between the interest rate on reserves and the fed funds rate because of this discrepancy between firms in the fed funds market and those with access to interest on reserves.

The central bank can still control the fed funds rate by changing the interest on reserve rate. An increase in the interest on reserves rate does change the incentive of banks, but the different market power means that this change will likely not happen in a one for one manner. However, Bech and Klee suggest that when the spread between the interest rates becomes too large, the central bank can still control the spread by draining reserves from the system. While this will not affect the firms getting interest on reserves, it will increase the interest rate charged by firms without access to interest on reserves. This occurs by changing the relative market share of these firms in the overnight market by reintroducing many of the banks earning interest on reserves to the overnight market. In short, Bech and Klee (2009) show that interest on reserves can still have many of the benefits espoused by Goodfriend (2002), like using open market operations to influence financial stability and the reserve rate to influence the real economy, but banks’ market power contributes significantly to how the spread between the IOR rate and the Fed Funds rate changes.
While the above models largely focus solely on interest on reserves, central banks can also control the ON RRP market rate. Armenter and Lester (2016) build on the above model by incorporating the concerns espoused in Bech and Klee (2009) about market power and having the central bank target the interest rate on reserves and the ON RRP rate. However, in their September 2014 press release\(^1\), the Federal Reserve expressed interest in phasing out the ON RRP market, so Armenter and Lester use this model to explore how much control the central bank can have over the fed funds market without an ON RRP market. Without an ON RRP market, the central bank struggles to raise the overnight lending market rate by raising the interest rate on reserves. Additionally, with a cap on the volume of ON RRP market, the fed funds rate dips outside the target range only in extreme circumstances. In this scenario, depository institutions have increased power in the fed funds market: if a depositor knows the lender cannot participate in the ON RRP market, they will offer a lower fed funds rate and the lender will have greater pressure to take it. Taken as a whole, Armenter and Lester show that with interest on reserves, the central bank must utilize its control in lending markets for it to be able to influence the fed funds rate.

While the above models largely focus on the fed funds market alone, G"untner (2015) nests a fed funds market into a real business cycle model with only financial frictions to examine the market in general equilibrium. In this model, banks face liquidity risk and voluntarily enter the fed funds market. Banks hold excess reserves as a precaution against liquidity risk and limited participation in the fed funds market, and fed funds lending emerges because of uncertainty about future deposits. While IOR and large excess reserve balances does not influence the transmission of traditional monetary policy, it does dull the transmission of quantitative easing. With the interest rate against the zero-lower bound, banks simply hold the additional reserves created by quantitative easing rather than lending. In turn, QE leads to a buildup of excess reserves and a decline in fed funds market participation.

Paying interest on reserves can also change how the economy reacts to changes in the size of the central bank’s balance sheet. Williamson (2018) develops a two sector banking model similar to

\(^1\)For more, see https://www.federalreserve.gov/newsevents/pressreleases/monetary20140917c.htm
Armenter and Lester (2016) and others described above to examine how paying interest on reserves changes how a bank operates given balance sheet costs. These banks face capital constraints, which restricts how much they can borrow. Further, many of these banks’ assets are used as collateral, so banks are further restricted when borrowing. Both the collateral and capital constraints can bind in equilibrium of Williamson’s model because there is a shortage of collateral created by governments facing tighter budget constraints, limiting the quantity of bonds. Many banks are holding reserves that are on the balance sheet of other banks, which is costly. In turn, a reduction in the size of a central bank’s balance sheet is welfare improving because it decreases the amount of reserves in the system, reducing this reserve-holding cost to banks and increasing the amount of collateral in the market. However, this can decrease liquidity in the financial sector, increasing risk. Further, with an introduction of an ON RRP facility into the model, a reduction in the size of the balance sheet continues to be welfare improving, but the ON RRP rate also puts a floor on the fed funds rate. A bank with excess reserves can choose to either hold these reserves and earn interest, lend in the fed funds market, or go to the ON RRP facility. A bank will not lend in the market if it can earn a greater return in through the ON RRP, thereby putting a lower bound on the fed funds rate. Additionally, an active ON RRP market decreases the spread between the fed funds rate and the interest rate on reserves. In Williamson’s model, the interest rate on reserves is higher than the fed funds rate, so the imposition of a floor in the ON RRP market can raise the fed funds rate and shrink the spread with the interest rate on reserves. The introduction of the ON RRP rate as an explicit floor of the fed funds rate brings this model closer to the belief set out in Armenter and Lester (2016) that the Federal Reserve can use the ON RRP facility to control the fed funds rate.

Finally, Dutkowsky and VanHoose (2020) note that, as the Fed began shrinking its balance sheet in 2017, depository institutions started to become lenders, as well as borrowers. The authors thus extend the above model to allow depository institutions to both lend and borrow in the fed funds market depending on their reserves holdings. In their model, banks choose to engage in interbank lending, as well as hold excess reserves. This, in turn, closes the spread between IOR and the fed funds rate, leaving banks indifferent between holding reserves and lending. This leads
retail bank lending to be *more* sensitive to changes in IOR and fed funds, but *less* sensitive to policies such as quantitative easing. Dutkowsky and VanHoose conclude by suggesting the Fed can target the IOR-fed funds spread by manipulating the quantity of reserves in the banking system again.

### 3.4 Current Policy Implementation

Ihrig et al. (2015, 2020) lay out the Federal Reserve’s perspective on policy under an interest on reserves regime. Ihrig et al. (2015) discuss that the Fed has five primary ways it can adjust interest rates. First, it can increase the interest rate on reserves. This encourages arbitrage between the fed funds rate and the reserve rate as banks attempt to borrow in the fed funds market to make a risk-free return. This puts an upward pressure on the fed funds rate as loaners can demand a higher return. While the Fed has the ability to pay interest on both required and excess reserves, interest on required reserves does not incentivize a bank to hold more reserves: they are required to hold that amount regardless of whether or not it pays interest. As such, the Fed’s primary policy tool is the interest rate on excess reserves. Next, the Fed can offer reverse repurchase agreements. This can also increase the scarcity of reserves as more reserves are used in the agreements. Third, they can offer term deposits. Similar to repurchase agreements, this encourages arbitrage among banks looking for a risk free return and decreases the quantity of reserves available to be loaned in the fed funds market. Fourth and fifth, the Fed can attempt to adjust the fed funds rate the way it did before 2008: by decreasing its security holdings or increasing the reserve requirements. This increases the scarcity of reserves in the system, thereby increasing the price of reserves. Because of the large quantity of reserves now in circulation, the Fed worries that it would have to decrease the quantity of reserves too substantially to return to its pre-crisis policy. As a result, while the Fed continues to target the overnight fed funds rate, it now largely does so through both changing the quantity of reserves by adjusting its security holdings and adjusting the interest rate on reserves, somewhat similar to the system laid out in Goodfriend (2002). Changing the interest rate on reserves allows
the Fed to adjust the Fed Funds rate without involvement in the market for reserves via open market operations. Given this, it is clear the interest rate on reserves is now a primary tool used by central banks to implement policy.

However, as Ihrig et al. (2020) discusses, the amount of reserves in the banking system affects the implementation of IOR. Ihrig et al. note the Fed prefers to set policy with an “ample reserves” approach where the market is satiated with reserves, similar to the proposal in Goodfriend (2002). In contrast, prior to the introduction of IOR in 2008, the Fed followed a “scarce reserves” regime which required the active management of reserves to set policy. This ample reserve regime allows the Fed to control interest rates without these daily interventions in reserves markets while still ensuring enough system-wide liquidity. However, the successful implementation of an ample reserve regime requires the Fed to carry a large balance sheet going forward, as well as remain vigilant to changes in the demand for reserves.

Dressler and Kersting (2015) take this examination a step further by incorporating a limited participation money market into a monetary DSGE model. In their model, banks can endogenously choose between holding excess reserves or lending out their reserves. Dressler and Kersting examine the implementation of IOR under these two regimes: a scarce reserve regime (where banks mostly only hold required reserves) and an ample reserve regime (where banks tend to hold many excess reserves). They find that monetary policy has a traditional effect under a scarce reserve regime. That is, a monetary contraction leads to a decline in output and inflation. However, in an ample reserve regime, a monetary contraction and increase in interest rates leads to a small increase in output and inflation. Put simply, in an ample reserve regime, a small decline in the quantity of reserves has little effect on a bank’s reserve constraint. Thus, banks choose to lend more to take advantage of higher interest rates. This leads to an unexpected result that higher interest rates lead to higher inflation through the Fisher Equation.

Using a similar model, Martin et al. (2019) argue that optimal policy in an abundant reserve regime must consider an optimal level of reserves, setting of the ON RRP rate, and setting of the IOR rate. The authors find that optimal reserve policy increases and decreases reserves to equate
bank deposit rates to IOR. Further, their model shows that optimal interest rate policy equates the ON RRP rate to the IOR rate. This, in turn, equalizes nearly all short-term interest rates, allowing banks to better absorb liquidity shocks and stabilizing short-term money markets.

This method of adjusting the fed funds rate through IOR and ON RRP in an abundant reserves system seemed to have settled the question of how monetary policy should be implemented through IOR. However, in late-2019, the fed funds market and other short-term interest rates began to spike above the Fed’s target, requiring daily Fed intervention. Copeland et al. (2020) found that, because of the Fed’s balance sheet normalization in 2017-2019 and new banking regulations, reserves had grown more scarce and dipped below an “efficient level” of reserves for an abundant reserve regime. Indeed, Copeland et al. conclude that these instabilities would not have occurred had there been more outstanding reserves in the banking system. Further, the authors say that, for an abundant reserve regime to efficiently operate with IOR, the Fed would need to consistently hold a larger balance sheet, relax many post-crisis liquidity regulations, and expand the usage of repo facilities and the discount window.

While questions remain about the day-to-day operations of monetary policy with IOR, Hamilton (2020) argues that, in the modern abundant reserve regime, the fed funds rate is divorced from its previous role as an indicator of liquidity in the banking system. Indeed, at lower frequencies, IOR and the fed funds rate are nearly perfectly correlated. This leads Dudley (2021) to argue that a fed funds rate target is obsolete as a policy tool, and the Fed should search for an alternative indicator of monetary policy.

While most papers have focused on the theory behind interest on reserves, recent work has begun to empirically test IOR’s effects. Hendrickson (2017) estimated how the introduction of IOR changed banks’ demand for reserves. He finds that IOR increased the demand for reserves. Further, this greater demand for reserves likely dulled the effect of quantitative easing, similar to the finding in Güntner (2015). Using call report data, Hogan (2021) finds that bank lending is

2Specifically, they have a .99 correlation coefficient at a monthly frequency
inversely related to the IOR rate, and that the introduction of IOR accounts for more than half of the decline in loans after the 2008 financial crisis.

3.5 Summary and Future Research Agenda

While many strides have been made in understanding interest on reserves, there is still more to learn. The papers thus far focus largely on understanding the modern structure of the fed funds market and how policy can be conducted with abundant reserves. However, the literature has yet to fully tackle at what level reserves become “abundant,” or whether there is a point at which there are too many reserves. Finding a consensus in how an abundant reserve regime should be conducted is among the first steps to a greater understanding of interest on reserves. Moreover, the fed funds market and excess reserves have similar maturities, but there is little examination into how this influences the term structure of interest rates throughout the economy. An examination into the response of financial markets and the yield curve will give a clearer picture of the ramifications of this new policy.

Taken together, future research should be three pronged. First, it should examine to a greater extent the asset allocation decisions banks make with interest on reserves. Banks will naturally allocate assets differently when reserves change from a non-interest bearing asset to an interest bearing asset or from scarce to abundant, and these decisions can affect how policy trickles down into the real economy. Second, the literature must find a greater understanding about how many reserves are necessary, as well as studying whether there can exist “too many” reserves for this regime to be effective. Finally, the future research should consider in greater detail the concerns of Hamilton (2020) and Dudley (2021) that the fed funds rate is no longer a sufficient indicator for monetary policy.
References


Gertler, M., & Karadi, P. (2018). Qe 1 vs. 2 vs. 3...: A framework for analyzing large-scale asset purchases as a monetary policy tool. 29th issue (January 2013) of the International Journal of Central Banking.


Appendix

A Appendix to Chapter 1

A.1 Bayesian Estimation Priors

The prior distributions, means, and standard deviations used in estimation, given in Table A.1, are similar to those used in Canova (2009) for the NK model. The slope of the IS curve, $\psi$, and Phillips Curve, $\kappa$, have gamma distributions with a prior mean of -.5 and 1, respectively. The inflation feedback parameter, $\beta$, has a beta distribution and a prior mean near a rational expectations benchmark at .98. The monetary parameters are set at $\rho = .8$, $\phi_y = .5$ and $\phi_\pi = 1.3$. Additionally, the prior for the inflation parameter, $\phi_\pi$ is truncated at 1 to not allow indeterminacy.

For the DSGE model, we use the same priors as Smets and Wouters (2007), given in Table A.2. The time preference rate is set at 0.25 (corresponding to $\beta = .9975$), the steady state inflation ($\bar{\pi}$) and growth rate ($\bar{\gamma}$) are set at 0.62 and and .4, respectively (corresponding to an annualized 2.5% inflation rate and 1.6% real growth rate). Steady state hours, $\bar{l}$, is set at 0, Firsh elasticity, $\sigma_\ell$, is 2, while risk aversion, $\sigma_c$, and habit formation, $\lambda$, are set at 1.5 and .7, respectively. The Calvo parameters, $\xi_p$ and $\xi_w$, are both .5, and wage and price indexation, ($\iota_p, \iota_w$) are also .5. Finally, capacity utilization, $\psi$, is set at .5, and the fixed cost and capital shares ($\Phi$ and $\alpha$) are 1.25 and .3, respectively. The monetary autoregressive parameter, $\rho$, is set at .75, and the monetary feedback parameters, $\phi_\pi$, $\phi_y$, $\phi_{\Delta y}$ are set at 1.5, .12, and .12, respectively. Similar to the NK model, the prior for $\phi_\pi$ is truncated at 1 to require determinacy.
A.2 Additional Diagnostics

This section reports and discusses results of additional diagnostic analyses for model estimation not included in Section 6.

Non-monetary Structural Shocks

The monetary structural shocks for the NK and DSGE models are shown in Figure 3 of Section 6. Here, Figure A.1 and Figure A.2 plot the non-monetary structural shocks from the NK ($\eta$) and DSGE models ($\varepsilon$). In addition to the model parameters, the shock structure is highly variable between periods. The variance ratios of the shocks can be found in Table A.3, and the autocorrelations are in Table A.4.

For the NK model, the relative variance of the output gap shock is larger than its full sample estimate in period I. It declines from the period I and period II (from 1.42 to .61), but increases substantially to 3.30 times the full sample shock variance in the final subperiod. On the other hand, the inflation shock is similarly unstable between periods I and II (1.36 and 1.63 times the full sample variance, respectively), but is considerably more stable in period III (.88 times the full sample variance), when inflation was more stable. The output gap shock’s persistence is largely stable between the Great Moderation and post-Crisis, shifting from .79 to .87. Meanwhile, The inflation shock is highly persistent and near unity in periods I and II. However, the persistence declines substantially in period III (from .99 to .65), corresponding to the lower variance in the inflation shock.

For the DSGE model, the shock structure is similarly unstable between subperiods. The productivity, risk premium, spending, investment, and price markup shocks each have a higher variance in period I than their full-sample estimates, varying from 2.19 (risk premium) to 1.11 (spending). Each then declines between period I and period II with the risk premium shock declining the most (from 2.19 to .76) and the spending shock declining the least (from 1.11 to .85). The wage markup shock has a lower variance in period I than its full sample estimate (.48), and the variance of the wage markup shock increases between periods I and II (to .80). The DSGE model
Table A.1: Estimation priors

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<th>Parameter Role</th>
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<th>Prior Mean</th>
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<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>$\kappa$</td>
<td>Phillips Curve slope</td>
<td>Gamma</td>
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</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>(2.00)</td>
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<tr>
<td></td>
<td>$\beta$</td>
<td>Inflation Expectation feedback</td>
<td>Beta</td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
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<td>$\rho$</td>
<td>Monetary smoothing</td>
<td>Beta</td>
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<td>(.25)</td>
</tr>
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<td>$\phi_\pi$</td>
<td>Taylor Rule: Inflation</td>
<td>Normal</td>
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<td></td>
<td></td>
<td>(.5)</td>
</tr>
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<td></td>
<td>$\phi_y$</td>
<td>Taylor Rule: Output</td>
<td>Beta</td>
<td>.5</td>
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<td>(.25)</td>
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Figure A.1: Structural shocks ($\eta$) from NK model
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<th>Prior Mean</th>
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<td></td>
<td>$\bar{\pi}$</td>
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<td>Gamma</td>
<td>.62 (.10)</td>
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<td></td>
<td>$\bar{\gamma}$</td>
<td>Steady State Growth Rate</td>
<td>Normal</td>
<td>.40 (.10)</td>
</tr>
<tr>
<td></td>
<td>$\bar{\ell}$</td>
<td>Steady State Hours</td>
<td>Normal</td>
<td>.00 (2.00)</td>
</tr>
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<td></td>
<td>$\rho$</td>
<td>Investment Adjustment Cost</td>
<td>Normal</td>
<td>4.00 (1.50)</td>
</tr>
<tr>
<td></td>
<td>$\sigma_c$</td>
<td>Risk Aversion</td>
<td>Normal</td>
<td>1.50 (.37)</td>
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<td></td>
<td>$\lambda$</td>
<td>External Habit Degree</td>
<td>Beta</td>
<td>.70 (.10)</td>
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<td>.50 (.10)</td>
</tr>
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<td>$\sigma_l$</td>
<td>Frisch Elasticity</td>
<td>Normal</td>
<td>2.00 (.75)</td>
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<td>Calvo Parameter: Prices</td>
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<td>.50 (.10)</td>
</tr>
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<td>$\iota_w$</td>
<td>Indexation to Past Wages</td>
<td>Beta</td>
<td>.50 (.15)</td>
</tr>
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<td>$\iota_p$</td>
<td>Indexation to Past Prices</td>
<td>Beta</td>
<td>.50 (.15)</td>
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<td>Capacity Utilization Cost</td>
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</tr>
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<td></td>
<td>$\Phi$</td>
<td>Fixed Cost Share</td>
<td>Normal</td>
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<td>$\alpha$</td>
<td>Capital Share</td>
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<td>Beta</td>
<td>.75 (.10)</td>
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<td>$\phi_{\pi}$</td>
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<td></td>
<td>$\phi_y$</td>
<td>Taylor Rule: Output</td>
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<td>.12 (.05)</td>
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<td></td>
<td>$\phi_{\Delta y}$</td>
<td>Taylor Rule: Growth</td>
<td>Normal</td>
<td>.12 (.05)</td>
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</table>
struggles to fit period III, as only the variance of the spending shock declines between periods II and III, declining from .85 to .64. The relative variance of the productivity and investment shocks increases the least (both from .78 to .95), while the relative variance of the wage markup shock increases the most (from .80 to 1.77). Only the persistence of the productivity and wage markup shocks decline between periods I and II (from .99 to .92 and from .94 to .78, respectively). The persistence of the spending shock increases the least (from .90 to .96) and the persistence of the risk premium shock increases the most (from .24 to .74). Alternatively, between periods II and III, only the risk premium shock becomes more persistent (from .74 to .79). While each remaining shock’s persistence declines in period III, the wage markup shock declines the most, from .78 to .21.
Table A.3: Structural shock standard deviation

<table>
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<td>FS</td>
<td>I</td>
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<td>VAR</td>
<td>$\sigma^y_t$</td>
<td>Output Gap</td>
<td>.74</td>
<td>1.25</td>
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<td></td>
<td>(.03)</td>
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</tr>
<tr>
<td></td>
<td>$\sigma^\pi_t$</td>
<td>Inflation</td>
<td>.31</td>
<td>1.28</td>
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<td></td>
<td></td>
<td></td>
<td>(.01)</td>
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<td>$\sigma^i_t$</td>
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<td>.78</td>
<td>1.43</td>
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<td>(.04)</td>
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<td>$\eta^\pi_t$</td>
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<td>$\eta^i_t$</td>
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<td>$\epsilon^m_t$</td>
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<td>.22</td>
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<td>$\epsilon^p_t$</td>
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Non-Monetary Impulse Responses

The main text focuses on the responses of the benchmark models to innovations in the monetary policy shock, which is common to all three models and directly relevant to the Taylor Rule. We do not include impulse responses to the other structural shocks here for two reasons. The non-monetary shocks are not easily compared across models and the sheer number of responses requires too much textual discussion. However, the full set of impulse responses is available upon request.
### Table A.4: Structural shock persistence

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<th>III</th>
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<td>[.42, .84]</td>
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<td>-.55</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>[.16, .45]</td>
<td>[.89, .99]</td>
<td>[.50, .97]</td>
<td>[.04, .37]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The VAR’s shock persistence is simply the autoregressive parameter from each equation in the model.

### Output Gaps

Extending the sample for the DSGE model from Smets and Wouter’s (2007) original estimation (red line ending in 2004) to our sample period (blue line ending in 2019) drastically changes the DSGE output gap, as shown in Figure A.3. The original DSGE gap (red line) is close to the CBO gap until the mid-1970s, when it fell well below the CBO gap before catching up to the CBO gap in the late 1980s. Adding 15 more years of data to the estimation largely resolves the discrepancy in the 1970s and 1980s. However, it introduces a new, even larger discrepancy between the DSGE and CBO gaps from the late 1980s through 2019 as noted in the main text.
B Appendix to Chapter 2

B.1 Decaying AIT

Under standard average inflation targeting, the central bank responds equally as strongly to current and past inflation. Instead, AIT could be implemented by incorporating a decay parameter on past inflation. In this scenario, I replace the inflation averaging \( \frac{1}{j} \sum_{j=1}^{j-1} \pi_{t-j} \) in equations (2.47), (2.48), and (2.49) with:

\[
\hat{\pi}_t = \omega \pi_t + (1 - \omega) \hat{\pi}_{t-1}
\]  

In this specification, agents can have imperfect information about the central bank’s decay parameter, \( \omega \), rather than the averaging window.

Similar to the specification discussed in section 5, imperfect information still leads to consistently higher variances in output and inflation, as well as lower utility. Under this specification,
inflation is most effectively stabilized when $\omega \approx 0.2$, so changes in inflation have a half-life of 4 quarters. The zero-lower bound incidence is minimized at a similar value of $\omega$. However, utility consistently declines as $\omega$ increases, so utility is maximized under a price-level target in this specification.

Under imperfect information, a similar theme holds: output is stabilized by targeting current inflation ($\omega = 1$), inflation and interest rates are stabilized with a moderate averaging, and utility is highest under a price level target. Importantly, similar to the earlier specification of AIT, the least effective full information policy still leads to higher utility than the most effective imperfect information policy, reiterating the importance of commitment and transparency to a policy by the central bank, and attentiveness to the policy by households and firms.

![Figure B.1: Total utility and ZLB frequency with decaying AIT.](image)

### B.2 Alternative QE

In the model laid out in section 3, the central bank can conduct quantitative easing by buying both government and private sector bonds. This is standard practice by both the BOJ and ECB, but the Fed only recently began purchasing corporate bonds under the provisions in the CARES
During the first 3 phases of QE from 2008-2014, the Fed conducted QE by purchasing only Treasury bonds and mortgage backed securities. To examine this policy more closely, I rerun the model simulations replacing equation 2.48 with:

\[ F_{cb,t} = \rho_F F_{cb,t-1} + (1 - \rho_F) F_{cb} + e_{F,t} \]

where \( F_{cb} \) is the central bank’s steady state holdings of private securities (assumed to be zero here).

![Results from Simulation](image)

Figure B.2: Total utility and ZLB frequency with alternative QE.

Interestingly, allowing the central bank to only buy government bonds leads to similar variances as the averaging window varies. Output is most stable when the central bank targets single-period inflation, while both inflation and the interest rate are most stable using a moderate length-averaging window. The zero-lower bound is also minimized under moderate-AIT. However, in this case, total utility is highest under single-period inflation targeting, and decreases steadily as the averaging window increases. Information has a similar effect to that in the earlier simulation: imperfect information leads to consistently higher variances and lower utility than full information.
Furthermore, allowing the central bank to conduct QE by only buying government bonds leads to a level shift in nearly every case: output and inflation are more stable when the central bank only buys government bonds. However, interest rates are considerably less stable, interest rates fall to zero more frequently, and total utility is lower when QE is conducted in this way.