BOARD OF GOVERNORS OF THE FEDERAL RESERVE SYSTEM
DIVISION OF MONETARY AFFAIRS
FOMC SECRETARIAT

Date: December 3, 2012

To: Research Directors

From: Deborah J. Danker

Subject: Supporting Documents for DSGE Models Update

The attached documents support the update on the projections of the DSGE models.

The Current Outlook and Alternative Policy Rule Simulations in EDO: December FOMC Meeting (Internal FR)

Hess Chung *

November 27, 2012

1 Introduction

This note describes the EDO forecast for 2012 to 2015, as well as a number of alternative monetary policy simulations in EDO, most undertaken as part of a special topic for the December Federal Reserve System DSGE project. Specifically, given the EDO baseline forecast, we consider several alternative dates for the departure of the federal funds rate from the zero lower bound. Taking as given the initial conditions underlying the EDO forecast, we then simulate the results of switching to three alternative rules: a representative Taylor-type rule and two level-targeting rules (nominal income and price level targeting). Finally, we repeat these exercises taking the October Tealbook projection as the baseline.

To summarize our qualitative results from these alternative rules simulations, we find that

1. Extensions of the period at the zero lower bound to periods where there is a considerable gap between the baseline and the effective lower bound can have strongly stimulative effects on both real activity, including unemployment, and inflation, even in the very short term.

2. This stimulative effect wanes rapidly after the end of forward guidance. Accordingly, for particularly adverse baselines, threshold-type rules may require additional forward guidance beyond the date at which the threshold is hit in order to be credible.

3. Given both the EDO and Tealbook baselines, the alternative Taylor-type rules considere here imply significantly higher real interest rates at medium and longer horizons and accordingly yield quite severe short-run contractionary effects.

4. By contrast, both targeting rules deliver strong stimulus to real activity with sharp increases in real GDP in the first year and very persistently positive output gaps thereafter.

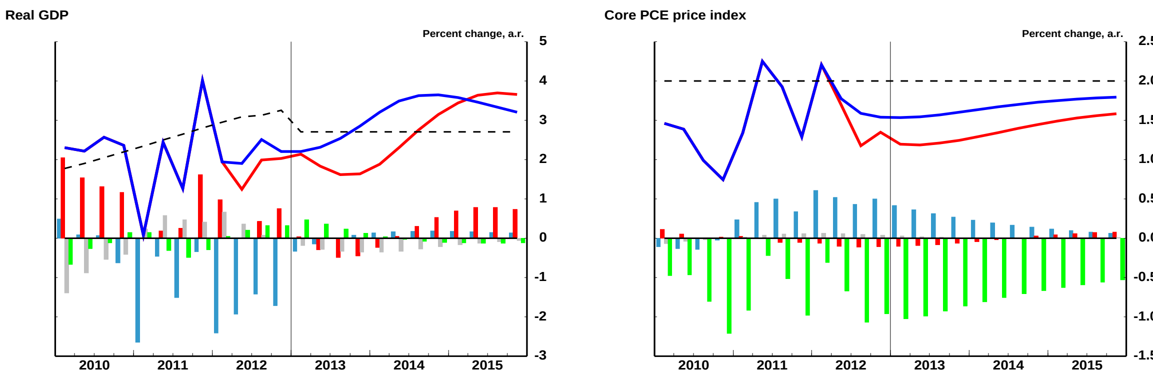
*Hess Chung (hess.t.chung@frb.gov)is affiliated with the Division of Research and Statistics of the Federal Reserve Board. Sections 4 and 5 contain background material on the EDO model, as in previous rounds. These sections were co-written with Michael Kiley and Jean-Philippe Laforte.

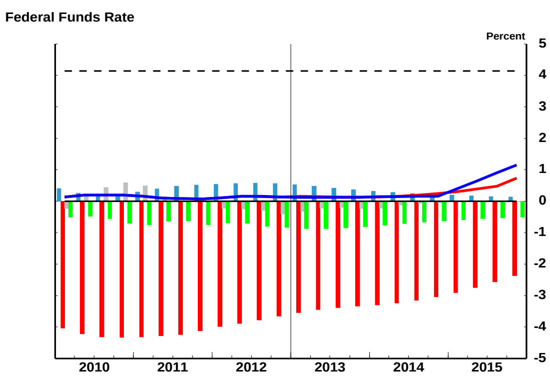
5. In the short-run, much of the stimulative power of the targeting rules, relative to the native EDO rule, can be accounted for by the implied extra-accommodative stance of monetary policy in the first 3 to 5 years of the simulation, after which the implied deviations from the native rule are modest, albeit not entirely negligible. [1]

2 The EDO Forecast from 2012 to 2015

Figure 1: Recent History and Forecasts

EDO Projection Summary





	2012 Q4/Q4	2013 Q4/Q4	2014 Q4/Q4	2015 Q4/Q4
Real GDP (a)	1.8	1.8	2.5	3.7
Credible set (c)	1.8-1.8	-1.7-4.9	.2-4.2	1.4-5.6
Core PCE Price index (a)	1.6	1.2	1.4	1.5
Credible set (c)	1.6-1.6	.6-1.8	.7-2.1	.9-2.4
Federal Funds Rate (b)	0.1	0.1	0.2	0.7
Credible set (c)	.1-.1	.0-1.5	.0-2.0	.0-2.5

(a) Q4/Q4 percent change, (b) Q4 level, (c) 68 percent

Red, solid line -- Data (through 2012:Q4) and projections; Blue, solid line -- Previous projection (September, 2012, as of 2012:Q2); Black, dashed line -- Steady-state or trend values
Contributions (bars): Red -- Financial; Blue -- Technology; Silver -- Monetary policy; Green -- Other

The baseline for these simulations consists of modal forecast trajectories from the EDO, conditional on the staff's October 2012 Tealbook projection through 2012:Q4 and OIS market expectations of the federal funds rate path through 2015:Q2. [2] The fourth quarter observation of these

[1] For instance, with the Tealbook baseline, the implied errors for both nominal income targeting and price level targeting fall are around one-half of the in-sample standard deviation of the monetary policy shock by the end of the fifth year of the simulation and go effectively to zero by 2024.

[2] Timing constraints on the preparation of the System Project materials made it infeasible to update the EDO projection to condition on the December 2012 Tealbook forecast, which was still in preparation as these materials were being finalized.

expectations was current as of November 7, 2012.

The baseline forecast,shown in Figure 1 projects below-trend real GDP growth and unemployment around 8 percent until early 2015. This subdued pace of real activity is accompanied by low inflation, slowly rising from 1.2 percent at the start of 2013 to 1.5 in 2015. Private agents do not expect the federal funds rate to lift appreciably above its effective lower bound until the first quarter of 2015.

The forecast is heavily shaped by the model's interpretation of the anticipated path of the federal funds rate, which has been persistently much lower than the model would have anticipated, given all other data. For the most part, the model accounts for this lower path by attributing to private agents the expectation of relatively adverse financial conditions over the forecast horizon. The aggregate risk premium remains in the neighborhood of its early 2012 levels, lowering GDP growth and boosting unemployment well above its steady-state. In addition, lower-than-expected labor productivity and surprisingly strong inflation since last year have led the model to infer a deterioration in aggregate supply conditions, which modestly reduces GDP growth early in the projection.

Given these adverse supply conditions, the path of the federal funds rate remains only slightly below the level consistent with the model's estimated policy rule, despite the weakness of aggregate demand in the forecast. Inflation is held below target by a combination of weak aggregate demand and muted pressure on wages in the labor market. Indeed, the unemployment rate rises slowly through early 2014, driven largely by the aforementioned weak demand conditions. By the end of the forecast, however, a substantial portion of the elevated unemployment rate is accounted for by a highly persistent shift in household labor supply, as is typical when the model is confronted by anomalously prolonged movements in unemployment.

3 Forward Guidance and Alternative Rule Monetary Policy Simulations

This section describes simulations of alternative monetary policy, given the fundamentals underlying the EDO forecast. The EDO baseline for these exercises is the expected trajectory, conditional on modal values for the model's static parameters. This baseline, shown in black in Figure 2, is very similar to the mean forecast described above.

3.1 The Effects of Forward Guidance

This section displays the effects of changes in the expected path of the federal funds rate, relative to the EDO baseline, on output, unemployment and inflation. Specifically, we consider the effects of maintaining the funds rate at the lower bound (12.5 basis points) for two and three additional quarters beyond baseline lift-off date (2015:Q1), defined as the earliest quarter after which the funds rate remains above 25 basis points.

As shown in Figure 2, under the baseline, the federal funds rate rises only gradually after lift-off. Accordingly, extending the time at the zero lower bound by three quarters has modest and fairly transient effects on real activity, with unemployment around 20 basis points below baseline through

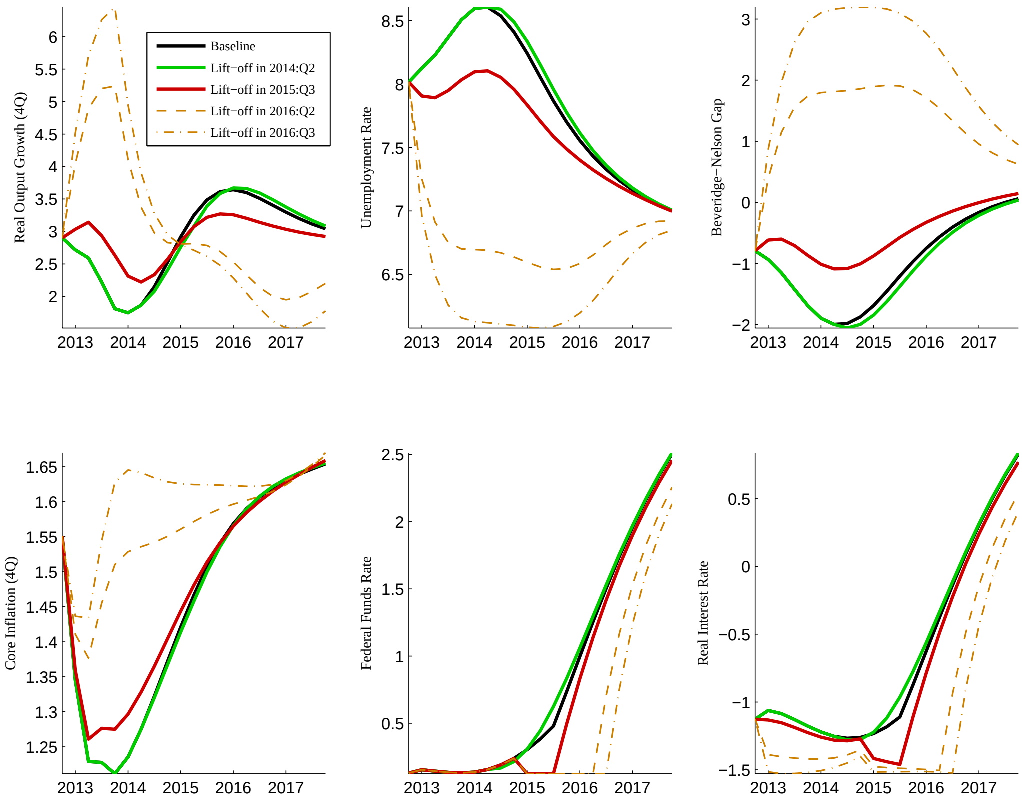


Figure 2: The effect of varying the date of lift-off from the zero lower bound, relative to the EDO baseline

mid-2015. At all horizons, the impact of additional forward guidance on inflation is negligible. As noted above, EDO attributes very little of the expected funds rate path to anticipated policy shocks. Accordingly, allowing the funds rate to lift-off earlier than the baseline has very little effect.

In many rational expectations models, over a certain horizon, successive extensions of the period at the zero lower bound have rapidly increasing short-run effects on both inflation and output. Two mechanisms underlie this amplification.

First, as shown in Figure 3, in the face of an anticipated reduction in the federal funds rate, inflation in the periods just before the realization of the shock is typically above steady-state, as wage and price setters move in advance of the expected higher inflation following the realization. As the same incentives confront earlier decision-makers, inflation and output over the entire period prior to the shock tends to be above steady-state, which implies higher peak inflation effects as the horizon is extended. Second, when the monetary policy authority has committed to remain at the zero lower bound at all earlier periods, this additional stimulus is not offset by increases in the federal funds rate and is accordingly amplified.

The strength of this amplification mechanism is visible in Figure 2, by a comparison of the output and inflation effects of foreward guidance until 2015:Q3 versus 2016:Q3 (yellow dash-dotted line).

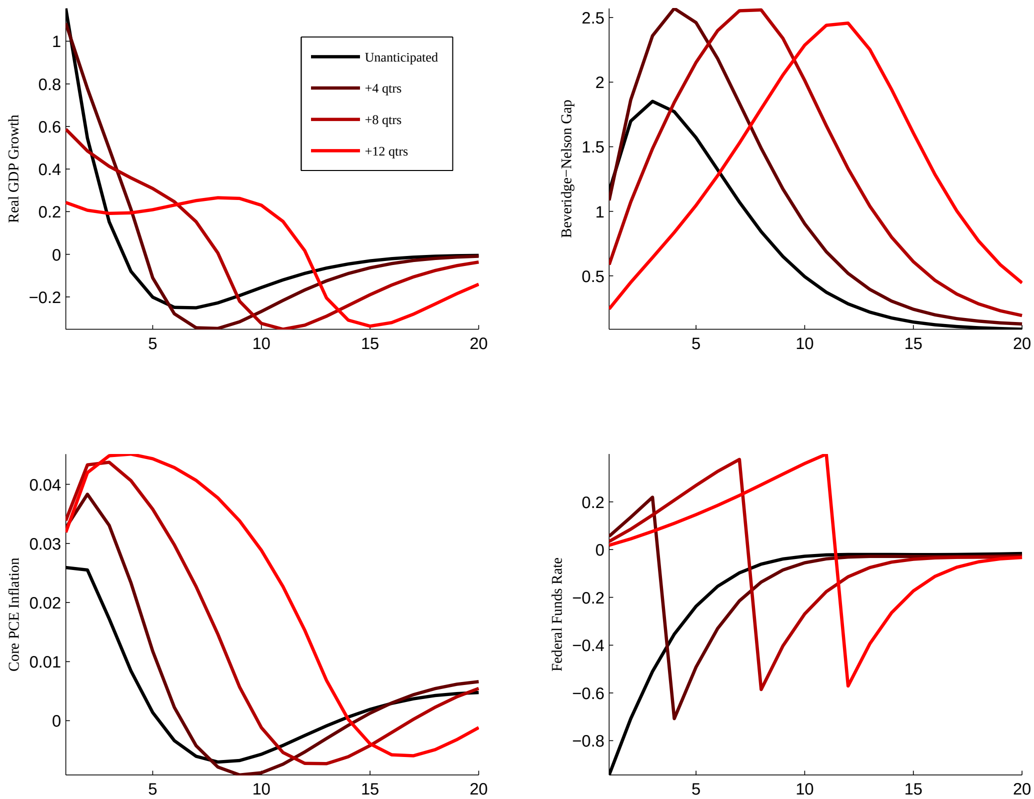


Figure 3: Impulse responses to anticipated reductions in the federal funds rate.

With an additional 4 quarters at the lower bound, the peak output response rises to around 6.25 percent, compared to the peak response of slightly above 3 percent for lift-off in 2015:Q3. The peak inflation effect is also around 30 basis points larger. The effect on unemployment is similarly marked, as unemployment drops smartly to around 6 percent by the beginning of 2014.

The close contemporaneous correlation between unemployment and activity, and the highly front-loaded response of both to anticipated policy shocks, has strong implications for the behavior of simple threshold rules in EDO. For example, a rule which mandates remaining at the zero lower bound until unemployment falls below 6.5 percent cannot lift off before 2016:Q2, given the EDO baseline, as shown by the dashed line in Figure 2. However, as noted above, remaining at the zero lower bound until 2016:Q3 causes unemployment to fall well below the threshold already at the beginning of 2014. It follows that, with this baseline, a credible threshold rule must also involve a good deal of foreward guidance for a number of quarters *after* the threshold is crossed.

3.2 Alternative Monetary Policy Rules

We were also asked to consider the effect of permanently changing the monetary policy rule, starting in 2013:Q1. The initial conditions are the same as in the EDO baseline forecast. The policy rules simulated are given as follows:

$$
\begin{array}{cc}
\text{(Hours rule)} & R_t = 0.75R_{t-1} + 0.25(2\bar{\pi}_t + 0.4Hours_t) \\
\text{(Nominal Income Target)} & R_t = .75R_{t-1} + 0.25NOMGAP_t \\
\text{(Price Level Target)} & R_t = .75R_{t-1} + 0.25(2PLGAP_t)
\end{array} \tag{1}
$$

where $\bar{\pi}_t$ is the 4-quarter moving average of core PCE inflation, $Hours_t$ is the deviation of aggregate hours worked from its steady-state. The nominal income gap ($NOMGAP_t$) is initialized at -7 in 2012:Q4, while the price level gap ($PLGAP_t$) is -1 in the same quarter.[3]

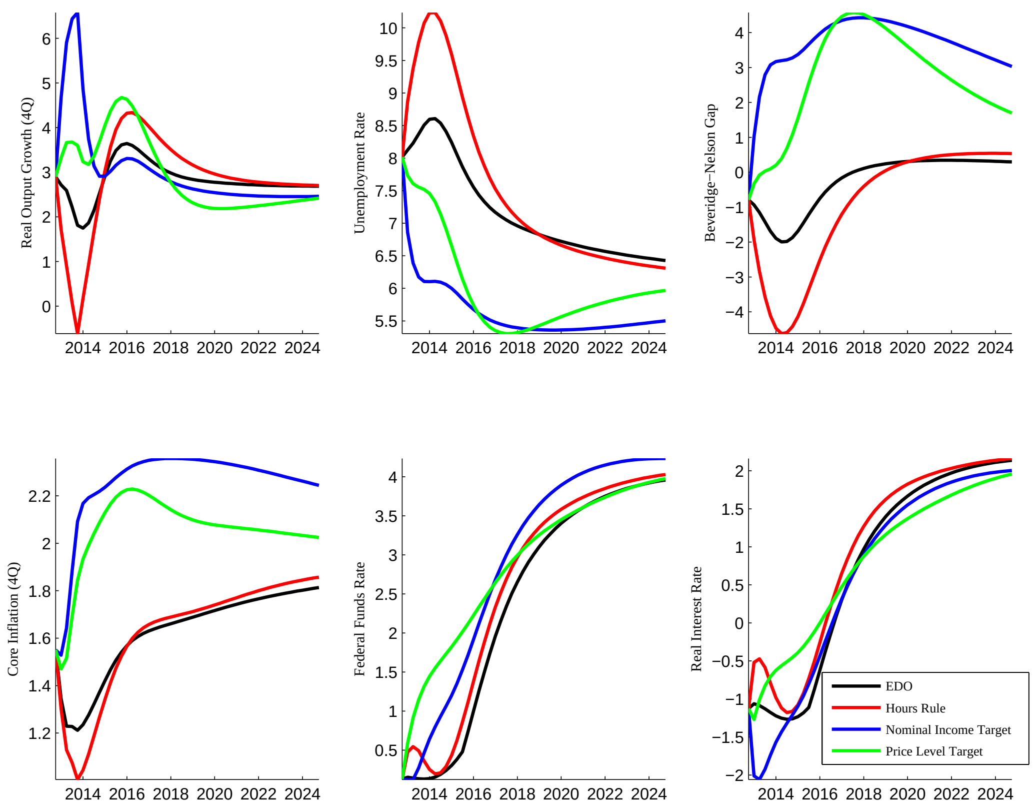


Figure 4: Simulations with alternative policy rules (EDO baseline initial conditions)

Figure 3.2 displays the equilibrium paths for selected variables under these alternative policy rules, given the initial conditions underlying the EDO baseline forecast. [4]

Under the hours rule, the federal funds rate rises permanently above the zero lower bound immediately. In part, the earlier lift-off for the hours rule is attributable to a relatively narrow hours gap (-1.5 percent in 2012:Q4) in the EDO forecast, about 50 basis points narrower than the production-function output gap on which the native rule depends. However, the hours rule also prescribes a meaningfully higher interest rate path for the first 4 to 5 years of the simulation than

[3]All variables in these rules are expressed in log-deviations from the steady-state, and the interest rates are annualized.

[4]Simulation of additional rules, including all those usually presented in the Tealbook, are presented in the Appendix. As shown there, Taylor-type rules produce results very similar to those obtained using the hours rule.

would the native rule. Moreover, real interest rates are higher over the entire first decade. As a result, short-run real activity is markedly depressed, with the Beveridge-Nelson gap widening by around 2.5 percentage points relative to baseline in 2013.

Under nominal income targeting, the federal funds rate lifts off in 2013:Q3, 6 quarters earlier than in the baseline. However, while the path of the funds rate is appreciably above baseline throughout the simulation, the rule allows for dramatically higher inflation, which rises above 2 percent by 2013:Q2, where it remains for duration of the simulation. Consequently, the real interest rate drops 1 percentage point below baseline immediately and continues to remain well below through the end of 2014. Real output rises around 3 percent above trend (around 4 percent above baseline) in 2013.

Under price level targeting, the federal funds rate rises sharply and permanently above the lower bound on , slightly earlier than under nominal income targeting. This rule brings inflation back to its long-run target relatively quickly, but the federal funds rate path in later years lies at baseline. The resulting real funds rate trajectory is thus below baseline for a number of years after 2018. As with nominal income targeting, the output gap becomes strongly positive, peaking at around 4.5 percent in 2017.

Some further insight into the behavior of the alternative equilibria can be gleaned from the following observation. Differences in outcomes between two equilibria differing only in the monetary policy rule can be completely accounted for by the contribution of the expected sequence of policy rule shocks in the baseline, with respect to the alternative rule. [5] Figure 3.2 accordingly decomposes the difference in the level of real output, inflation and real interest rates between the baseline and several of the alternative rules. [6]

As shown by the top left panel of the Figure, almost all of the sharp short-run decline in output under the hours rule, relative to the native rule, can be traced back to the tighter stance of monetary policy from 2013 through 2015. These shocks also account for almost all of the increase in the path of the real funds rate, with the peak effects on both real activity and real rates occuring contemporaneously.

In the case of the hours rule, output gap and inflation outcomes converge back to baseline by 2018 or so, and so longer-horizon shocks play little role in accounting for the difference between equilibria. However, under nominal income targeting, the output gap is still almost 3 percent above trend in 2024, while the funds rate is roughly at steady-state. Accordingly, long-horizon shocks relative to the native rule are much larger than for the hours rule and these shocks account for the very slow return of the output to trend under nominal income targeting. The presence of these shocks is of little importance for the outcomes before 2015, but do account for the very slow closure

[5] This statement assumes that the baseline equilibrium is unique. It follows then that the baseline must be reproduced under the alternative policy rule with anticipated setting policy shocks chosen such that the error for the baseline rule in the resulting equilibrium is zero. (If the alternative equilibrium is unique, such a sequence of shocks can always be chosen.) If it were not so, then there would be multiple sequences satisfying the baseline model's equilibrium conditions, contradicting the assumption of uniqueness. Because the model is linear, however, it then follows that the difference between the two equilibrium is completely captured by the effect of the policy rule shocks and, moreover, the policy shocks capturing this difference can be calculated using the reaction function errors in the baseline, under the alternative policy rule.

[6] Note that these decompositions cannot be interpreted as showing the effects of a temporary commitment to the alternative rule, as the shocks implementing the temporary commitment equilibrium will typically differ at all horizons from those implementing a permanent regime change.

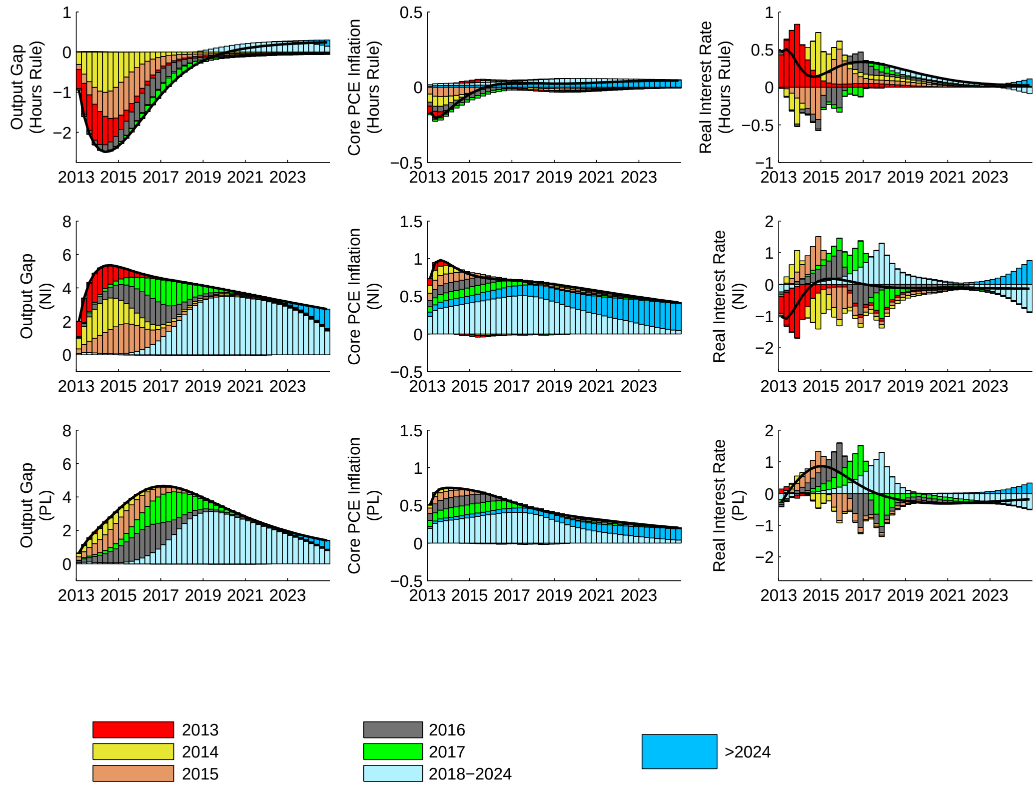


Figure 5: Decomposition of the difference in the level of real output and real federal funds rate between the EDO baseline and selected alternative equilibria.

of the output gap.

On the other hand, anticipated monetary policy shocks at long horizons can have comparatively strong effects on near-term inflation. Even when the effects on the real economy phase in gradually, wages and prices, which, in EDO, display only modest indexation, respond noticeably on impact to the anticipated lower path for marginal costs. Indeed, shocks at long horizons (after 2018) account for around half of the inflation effect in the early years of the simulation.

Under price level targeting, significant deviations from the native rule emerge only in 2015. As with nominal income targeting, the short-run inflation response features strong contributions from anticipated shocks at long horizons.

3.3 Alternative Rules Simulations around the Tealbook Baseline

This section describes alternative rules simulations, using EDO dynamics, around the October Tealbook baseline. In addition to providing comparability with the usual Tealbook rules simulations in FRB/US, these exercises may help bring out features of the alternative rules in EDO which are obscurred by some features of the EDO baseline forecast. In particular, the EDO forecast features a relatively narrow output gap path, albeit one which closes quite slowly, and very high unemployment towards the end of the forecast. Conducting the alternative simulations around the Tealbook forecast may help to identify features of the alternative rules which are robust to changes in these somewhat idiosyncratic features of the EDO baseline.

Forward guidance experiments similar to those reported above for the EDO baseline are shown in Figure 3.3. [7]

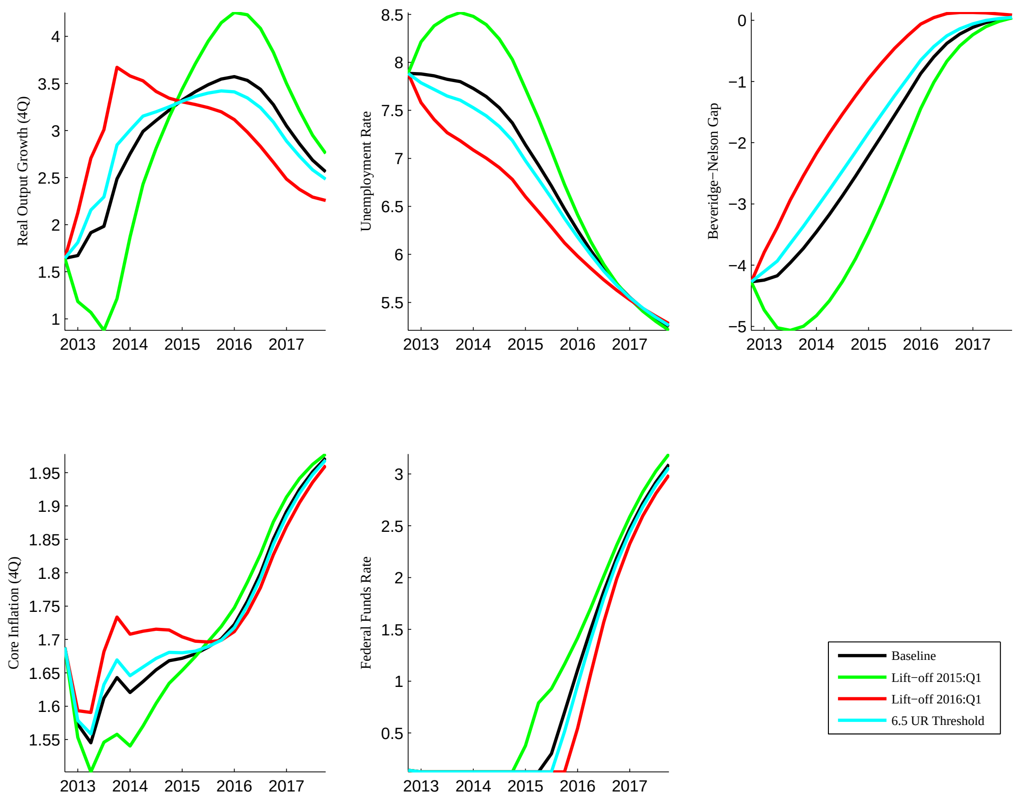


Figure 6: The effect of varying the date of lift-off from the zero lower bound, relative to the October Tealbook baseline

By 2015, the federal funds rate is well below the level implied by the outcome-based rule and, accordingly, reverting to this rule two quarters earlier than in the baseline (2015:Q1 versus 2015:Q3) entails a fair degree of drag on real activity, with the output gap widening around 1.5 percentage points by late 2013 and unemployment rising around 50 basis points in the same period. The output gap and unemployment rate have largely converged back to baseline by the beginning of 2016. An

[7] As described above, we characterize deviations from baseline through the implied monetary policy reaction function errors, under the alternative specification of monetary policy. We are accordingly able to remain agnostic about the particular sequence of anticipated shocks which rationalize the Tealbook baseline. However, for the alternative rules simulations, we are required to choose a finite horizon for the shock paths. We choose to use the extended Tealbook baseline constructed for Tealbook optimal control simulations in FRB/US, running through 2100. Such a long shock series is necessary to capture the permanent deviations from the rule which are implied by the baseline, as seen through level-targeting rules. We assume that the behavior of the federal funds rate is given by the outcome-based rule. Off baseline, the dynamics of the staff output gap are proxied by the Beveridge-Nelson gap. Initial nominal income and price level gaps are the same as used in the EDO baseline simulations.

additional two quarters at the zero-lower bound (2016:Q1,the red line) raises the output gap by around 1.25 percentage points at the start of 2014. The asymmetry between early and late lift-offs is accounted for the fact that the policy rule shocks removed by early lift-off are significantly larger than those generated in 2015:Q3 and 2015:Q4 by additional forward guidance. As with the EDO simulations, changes in foreward guidance of these magnitudes have little effect on inflation.

The blue line in Figure 3.3 show the path induced by a simple threshold rule which mandates remaining at the zero lower bound until unemployment falls below 6.5 percent. The threshold rule prescribes remaining at the zero bound until 2015:Q2, one quarter later than in the baseline. As discussed previously, given the unusually slow lift-off in the baseline, the threshold rule provides little additional stimulus to real activity.

We now present alternative rule simulations for a number of the policy rules usually featured in the Tealbook, as well as for price level targeting. Results are shown in Figure 3.3

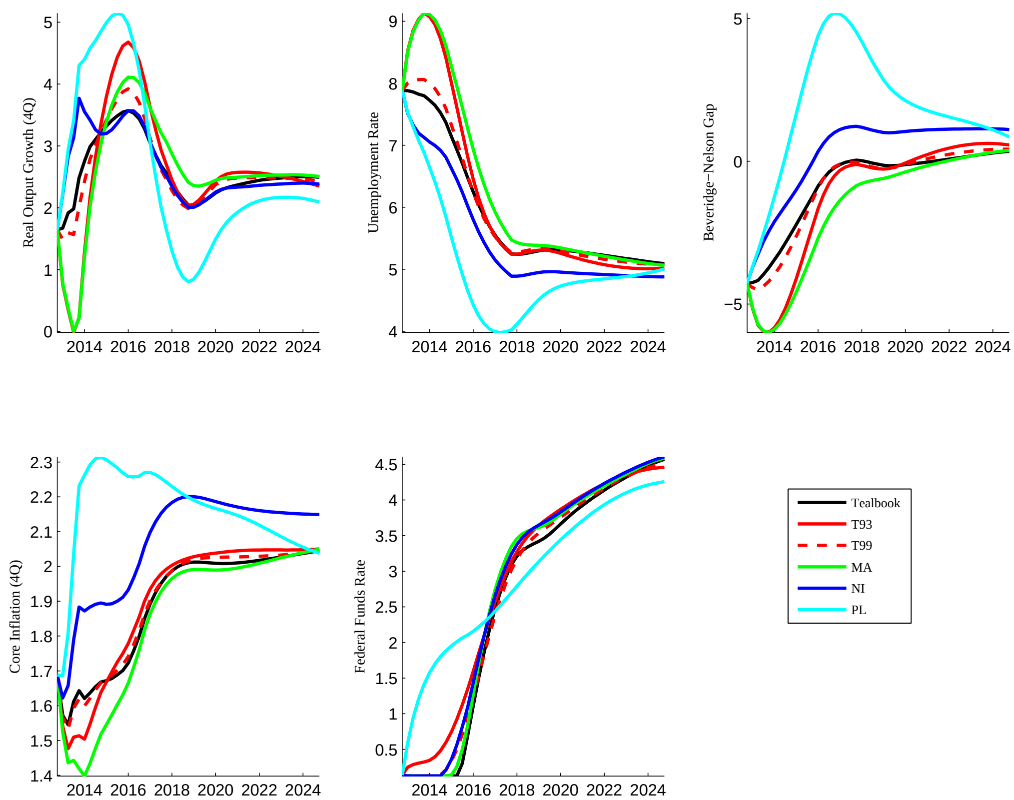


Figure 7: Alternative monetary policy rule simulations (October Tealbook baseline)

All Taylor-type rules leave the zero lower bound permanently before the baseline path. As a result, all imply weaker activity through 2016 or early 2017. The outcome-based rule, while it lifts off only a quarter ahead of the baseline, quickly overshoots the baseline path and remains higher thereafter. As a result, unemployment is more than 1.5 percentage point higher by late 2013, while inflation falls slightly. Although the Taylor 99 rule implies even earlier lift-off, the funds rate path converges quickly to the baseline and even undershoots in 2017 and 2018. Consequently, the impact of the earlier lift-off on real activity is modest.

As with the EDO baseline, given the October Tealbook baseline, nominal income and price level targets have considerably different implications for the funds rate path, and thus for real activity and inflation. However, while the price level targeting rule delivers broadly similar outcomes in both baselines, nominal income targeting is notably less stimulative given the Tealbook projection. This difference emerges from the fact that, while real activity is considerably stronger in the Tealbook than in the EDO forecast, especially in the early years, both projections for GDP inflation are similar through 2016 and thereafter diverge by only around 40-50 basis points. Accordingly, nominal income gap is notably narrower in the Tealbook baseline and, consequently, the nominal income targeting rule prescribes a lower degree of accommodation. By contrast, the price level targeting rule confronts a path for the price level gap which evolves similarly in both projections and accordingly provides a similar boost, relative to its baseline.

As in the previous section, the effect of switching to one of the targeting rules can be accounted for in terms of differences in reaction function shocks, relative to the baseline. Such a decomposition is present in Figure 3.3. A comparison between the nominal income targeting row of Figure 3.3 and the corresponding row of Figure 3.2 suggests that the timing of the additional stimulus delivered by the nominal income rule is broadly similar for both EDO and Tealbook baselines.

The real activity effect of switching to price level targeting is also quite similar, for both projections, although the Tealbook baseline implies somewhat more accomodation in 2015 through 2017. The response of core inflation is also quite similar, although shocks after 2018 account for a greater share of the short-run response in the EDO baseline than in the Tealbook.

4 An Overview of Key Model Features

Figure 9 provides a graphical overview of the model. While similar to most related models, EDO has a more detailed description of production and expenditure than most other models.[8]

Specifically, the model possesses two final good sectors in order to capture key long-run growth facts and to differentiate between the cyclical properties of different categories of durable expenditure (e.g., housing, consumer durables, and nonresidential investment). For example, technological progress has been faster in the production of business capital and consumer durables (such as computers and electronics).

The disaggregation of production (aggregate supply) leads naturally to some disaggregation of expenditures (aggregate demand). We move beyond the typical model with just two categories of (private domestic) demand (consumption and investment) and distinguish between four categories of private demand: consumer non-durable goods and non-housing services, consumer durable goods, residential investment, and non-residential investment. The boxes surrounding the producers in the figure illustrate how we structure the sources of each demand category. Consumer non-durable goods and services are sold directly to households; consumer durable goods, residential capital goods, and

[8] Chung, Kiley, and Laforte (2011) provide much more detail regarding the model specification, estimated parameters, and model propeties.

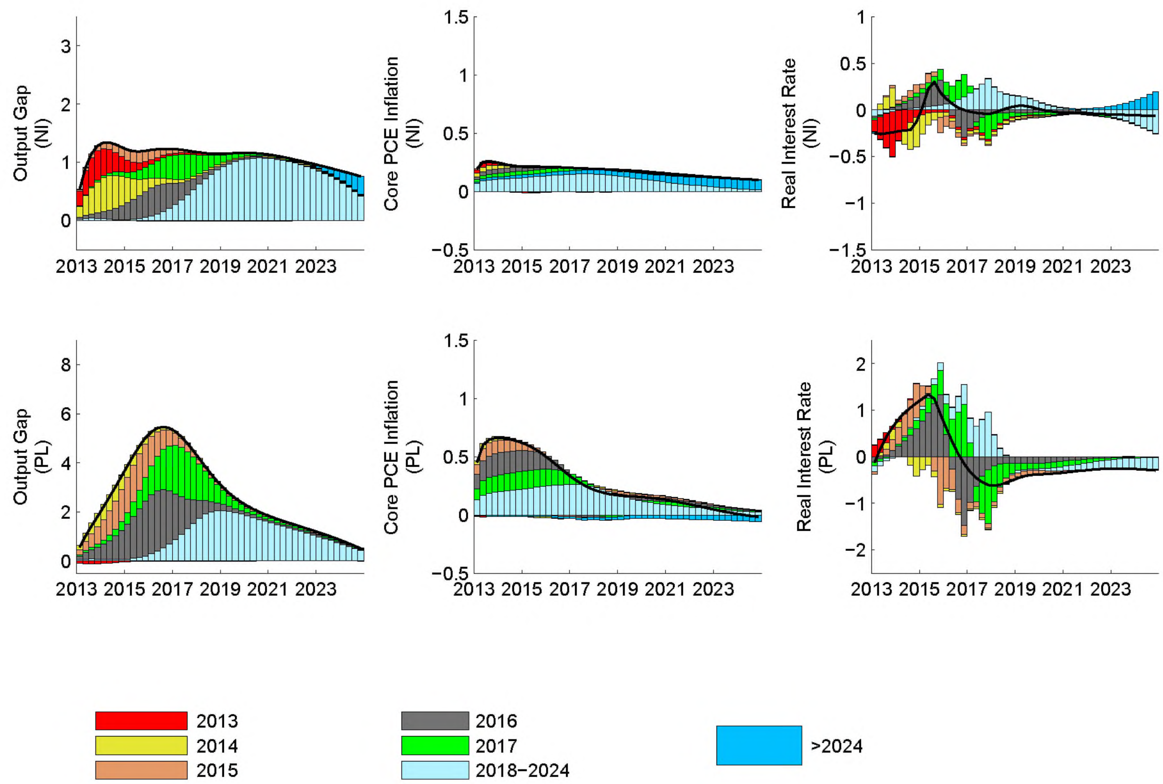


Figure 8: Decomposition of the difference in the level of real output and real federal funds rate between the October Tealbook baseline and selected alternative equilibria.

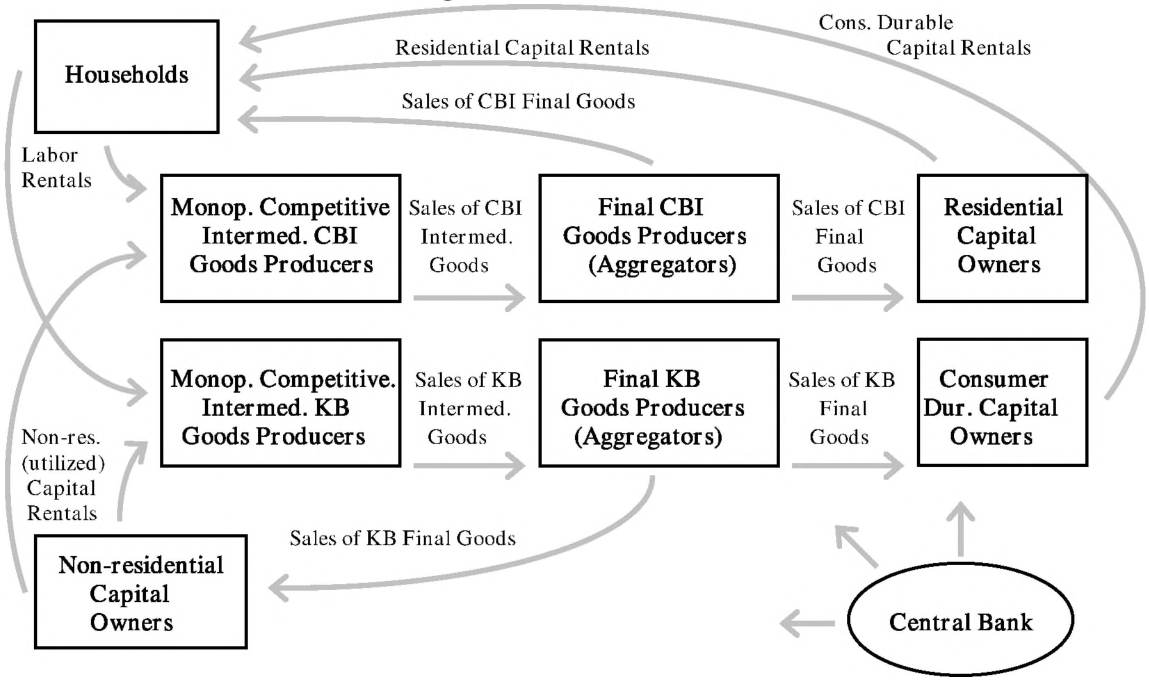
non-residential capital goods are intermediated through capital-goods intermediaries (owned by the households), who then rent these capital stocks to households. Consumer non-durable goods and services and residential capital goods are purchased (by households and residential capital goods owners, respectively) from the first of economy's two final goods producing sectors, while consumer durable goods and non-residential capital goods are purchased (by consumer durable and residential capital goods owners, respectively) from the second sector. In addition to consuming the non-durable goods and services that they purchase, households supply labor to the intermediate goods-producing firms in both sectors of the economy.

This remainder of this section provides an overview of the key properties of the model. In particular, the model has five key features:

- A new-Keynesian structure for price and wage dynamics. Unemployment measures the difference between the amount workers are willing to be employed and firms' employment demand. As a result, unemployment is an indicator of wage, and hence price, pressures, as in Gali (2010).

- Production of goods and services occurs in two sectors, with differential rates of technological

Figure 9: Model Overview



progress across sectors. In particular, productivity growth in the investment and consumer durable goods sector exceeds that in the production of other goods and services, helping the model match facts regarding long-run growth and relative price movements.

- A disaggregated specification of household preferences and firm production processes that leads to separate modeling of nondurables and services consumption, durables consumption, residential investment, and business investment.

- Risk premia associated with different investment decisions play a central role in the model. These include A) an aggregate risk-premium, or natural rate of interest, shock driving a wedge between the short-term policy rate and the interest rate facing private decisionmakers (as in Smets and Wouters (2007)) and B) fluctuations in the discount factor/risk premia facing the intermediaries financing household (residential and consumer durable) and business investment.

4.1 Two-sector production structure

It is well known (e.g., Edge, Kiley, and Laforte (2008)) that real outlays for business investment and consumer durables have substantially outpaced those on other goods and services, while the prices of these goods (relative to others) has fallen. For example, real outlays on consumer durables have far outpaced those on other consumption, while prices for consumer durables have been flat and those for other consumption have risen substantially; as a result, the ratio of nominal outlays in the two categories has been much more stable, although consumer durable outlays plummeted in the Great Recession. Many models fail to account for this fact.

EDO accounts for this development by assuming that business investment and consumer durables are produced in one sector and other goods and services in another sector. Specifically, production by firm j in each sector s (where s equals kb for the sector producing business investment and consumer durables sector and cbi for the sector producing other goods and services) is governed by a Cobb-Douglas production function with sector-specific technologies:

$$X_t^s(j) \; = \left(Z_t^m Z_t^s L_t^s(j)\right)^{1-\alpha} \left(K_t^{u,nr,s}(j)\right)^{\alpha}, \text{ for } s = cbi, kb. \tag{2}$$

In 2, Z^m represents (labor-augmenting) aggregate technology, while Z^s represents (labor-augmenting) sector-specific technology; we assume that sector-specific technological change affects the business investment and consumer durables sector only; L^s is labor input and $K^{u,nr,s}$ is capital input (that is, utilized *non-residential business* capital (and hence the nr and u terms in the superscript). Growth in this sector-specific technology accounts for the long-run trends, while high-frequency fluctuations allow the possibility that investment-specific technological change is a source of business cycle fluctuations, as in Fisher (2006).

4.2 The structure of demand

EDO differentiates between several categories of expenditure. Specifically, business investment spending determines non-residential capital used in production, and households value consumer nondurables goods and services, consumer durable goods, and residential capital (e.g., housing). Differentiation across these categories is important, as fluctuations in these categories of expenditure can differ notably, with the cycles in housing and business investment, for example, occurring at different points over the last three decades.

Valuations of these goods and services, in terms of household utility, is given by the following utility function:

$$\begin{aligned}\mathcal{E}_0 \sum_{t=0}^{\infty} \beta^t \Big\{ & \varsigma^{cnn} \ln(E_t^{cnn}(i) - hE_{t-1}^{cnn}(i)) + \varsigma^{cd} \ln(K_t^{cd}(i)) \\ & + \varsigma^r \ln(K_t^r(i)) \; - \varsigma^l \frac{(L_t^{cbi}(i) + L_t^{kb}(i))^{1+\nu}}{1+\nu} \Big\},\end{aligned} \tag{3}$$

where E^{cnn} represents expenditures on consumption of nondurable goods and services, K^{cd} and K^r represent the stocks of consumer durables and residential capital (housing), $L^{cbi} + L^{kb}$ represents the sum of labor supplied to each productive sector (with hours worked causing disutility), and the remaining terms represent parameters (such as the discount factor, relative value in utility of each service flow, and the elasticity of labor supply).

By modeling preferences over these disaggregated categories of expenditure, EDO attempts to account for the disparate forces driving consumption of nondurables and durables, residential investment, and business investment – thereby speaking to issues such as the surge in business investment in the second half of the 1990s or the housing cycle the early 2000s recession and the most recent downturn. Many other models do not distinguish between developments across these categories of spending.

4.3 Risk premia, financial shocks, and economic fluctuations

The structure of the EDO model implies that households value durable stocks according to their expected returns, including any expected service flows, and according to their risk characteristics, with a premium on assets which have high expected returns in adverse states of the world. However, the behaviour of models such as EDO is conventionally characterized under the assumption that this second component is negligible. In the absence of risk adjustment, the model would then imply that households adjust their portfolios until expected returns on all assets are equal.

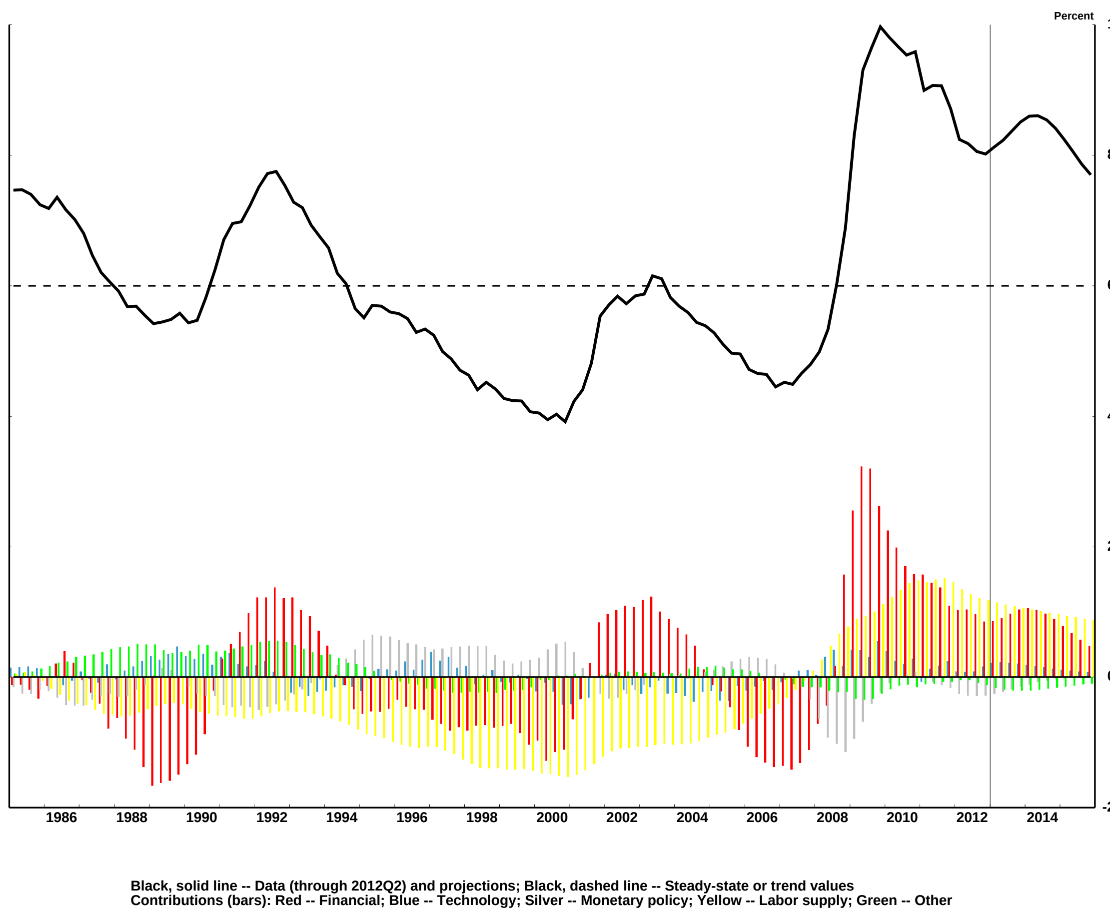
Empirically, however, this risk adjustment may not be negligible and, moreover, there may be a variety of factors, not explicitly modelled in EDO, which limit the ability of households to arbitrage away expected return differentials across different assets. To account for this possibility, EDO features several exogenous shocks to the rates of return required by the household to hold the assets in question. Following such a shock – an increase in the premium on a given asset, for example– households will wish to alter their portfolio composition to favor the affected asset, leading to changes in the prices of all assets and, ultimately, to changes in the expected path of production underlying these claims.

The "sector-specific" risk shocks affect the composition of spending more than the path of GDP itself. This occurs because a shock to these premia leads to sizable substitution across residential, consumer durable, and business investment; for example, an increase in the risk premia on residential investment leads households to shift away from residential investment and towards other types of productive investment. Consequently, it is intuitive that a large fraction of the non-cyclical, or idiosyncratic, component of investment flows to physical stocks will be accounted for by movements in the associated premia.

Shocks to the required rate of return on the nominal risk-free asset play an especially large role in EDO. Following an increase in the premium, in the absence of nominal rigidities, the households' desire for higher real holdings of the risk-free asset would be satisfied entirely by a fall in prices, i.e., the premium is a shock to the natural rate of interest. Given nominal rigidities, however, the desire for higher risk-free savings must be off-set, in part, through a fall in real income, a decline which is distributed across all spending components. Because this response is capable of generating comovement across spending categories, the model naturally exploits such shocks to explain the business cycle. Reflecting this role, we denote this shock as the "aggregate risk-premium".

Movements in financial markets and economic activity in recent years have made clear the role that frictions in financial markets play in economic fluctuations. This role was apparent much earlier, motivating a large body of research (e.g.,Bernanke, Gertler, and Gilchrist (1999)). While the range of frameworks used to incorporate such frictions has varied across researchers studying different questions, a common theme is that imperfections in financial markets – for example, related to imperfect information on the outlook for investment projects or earnings of borrowers – drives a wedge between the cost of riskless funds and the cost of funds facing households and firms. Much of the literature on financial frictions has worked to develop frameworks in which risk premia fluctuate for endogenous reasons (e.g., because of movements in the net worth of borrowers). Because the risk-premium shocks induces a wedge between the short-term nominal risk-free rate and the rate of return on the affected risky rates, these shocks may thus also be interpreted as a reflection of financial frictions not explicitly modelled in EDO. The sector-specific risk premia in EDO enter the model in much the same way as does the exogenous component of risk premia in models with some endogenous mechanism (such as the financial accelerator framework used Boivin, Kiley, and Mishkin (2010)), and the exogenous component is quantitatively the most significant one in that research.[9]

Figure 10: Unemployment Fluctuations in the EDO model



[9]Specifically, the risk premia enter EDO to a first-order (log)linear approximation in the same way as in the cited research if the parameter on net worth in the equation determining the borrowers cost of funds is set to zero; in practice, this parameter is often fairly small in financial accelerator models.

4.4 Unemployment Fluctuations in the EDO model

This version of the EDO model assumes that labor input consists of both employment and hours per worker. Workers differ in the disutility they associate with employment. Moreover, the labor market is characterized by monopolistic competition. As a result, unemployment arises in equilibrium – some workers are willing to be employed at the prevailing wage rate, but cannot find employment because firms are unwilling to hire additonal workers at the prevailing wage.

As emphasized by Gali (2010), this framework for unemployment is simple and implies that the unemployment rate reflects wage pressures: When the unemployment rate is unusually high, the prevailing wage rate exceeds the marginal rate of subsitution between leisure and consumption, implying that workers would prefer to work more.

In addition, in our environment, nominal wage adjustment is sticky, and this slow adjustment of wages implies that the economy can experience sizable swings in unemployment with only slow wage adjustment. Our specific implementation of the wage adjustment process yields a relatively standard New-Keynesian wage Phillips curve. The presence of both price and wage rigidities implies that stabilization of inflation is not, in general, the best possible policy objective (although a primary role for price stability in policy objectives remains).

While the specific model on unemployment is suitable for discussions of the links between unemployment and wage/price inflation, it leaves out many features of labor market dynamics. Most notably, it does not consider separations, hires, and vacancies, and is hence not amenable to analysis of issues related to the Beveridge curve.

As emphasized above, the rise in unemployment during the Great Recession primarily reflected, according to the EDO model, the weak demand that arose from elevated risk premiums that depressed spending, as illustrated by the red bars in figure 10.

Indeed, these demand factors explain the overwhelming share of cyclical movements in unemployment over the past two-and-a-half decades, as is also apparent in figure 10. Other factors are important for some other periods. For example, monetary policymakers lowered the federal funds rate rapidly over the course of 2008, somewhat in advance of the rise in unemployment and decline in inflation that followed. As illustrated by the silver bars in figure 10, these policy moves mitigated the rise in unemployment somewhat over 2009; however, monetary policy efforts provided less stimulus, according to EDO, over 2010 and 2011 – when the federal funds rate was constrained from falling further. (As in many other DSGE models, EDO does not include economic mechanisms through which quantitative easing provides stimulus to aggregate demand).

The contribution of supply shocks – most notably labor supply shocks – is also estimated to contribute importantly to the low-frequency movements in unemployment, as shown by the yellow bars in figure 10. Specifically, favorable supply developments in the labor market are estimated to have placed downward pressure on unemployment during the second half of the 1990s; these developments have reversed, and some of the currently elevated rate of unemployment is, according to EDO, attributable to adverse labor market supply developments. As discussed previously, these developments are simply exogenous within EDO and are not informed by data on a range of labor market developments (such as gross worker flows and vacancies).

4.5 New-Keynesian Price and Wage Phillips Curves

As in most of the related literature, nominal prices and wages are both "sticky" in EDO. This friction implies that nominal disturbances – that is, changes in monetary policy – have effects on real economic activity. In addition, the presence of both price and wage rigidities implies that stabilization of inflation is not, in general, the best possible policy objective (although a primary role for price stability in policy objectives remains).

Given the widespread use of the New-Keynesian Phillips curve, it is perhaps easiest to consider the form of the price and wage Phillips curves in EDO at the estimated parameters. The price Phillips curve (governing price adjustment in both productive sectors) has the form:

$$\pi_t^{p,s} = 0.22\pi_{t-1}^{p,s} + 0.76E_t\pi_{t+1}^{p,s} + .017mc_t^s + \theta_t^s \tag{4}$$

where mc is marginal cost and θ is a markup shock. As the parameters indicate, inflation is primarily forward-looking in EDO.

The wage (w) Phillips curve for each sector has the form:

$$\triangle w_t^s = 0.01\triangle w_{t-1}^s + 0.95E_t\triangle w_{t+1}^s + .012\left(mrs_t^{c,l} - w_t^s\right) + \theta_t^w + adj.\,costs. \tag{5}$$

where mrs represents the marginal rate of substitution between consumption and leisure. Wages are primarily forward looking and relatively insensitive to the gap between households' valuation of time spent working and the wage.

The middle panel of figure 1 presents the decomposition of inflation fluctuations into the exogenous disturbances that enter the EDO model. As can be seen, aggregate demand fluctuations, including aggregate risk premiums and monetary policy surprises, contribute little to the fluctuations in inflation according to the model. This is not surprising: In modern DSGE models, transitory demand disturbances do not lead to an unmooring of inflation (so long as monetary policy responds systematically to inflation and remains committed to price stability). In the short run, inflation fluctuations primarily reflect transitory price and wage shocks, or markup shocks in the language of EDO. Technological developments can also exert persistent pressure on costs, most notably during and following the strong productivity performance of the second half of the 1990s which is estimated to have lowered marginal costs and inflation through the early 2000s. More recently, disappointing labor productivity readings over the course of 2011 have led the model to infer sizeable negative technology shocks in both sectors, contributing noticeably to inflationary pressure over that period (as illustrated by the blue bars in figure 1),

4.6 Monetary Authority and A Long-term Interest Rate

We now turn to the last agent in our model, the monetary authority. It sets monetary policy in accordance with an Taylor-type interest-rate feedback rule. Policymakers smoothly adjust the actual interest rate R_t to its target level $\bar{R}_t$

$$R_t = (R_{t-1})^{\rho^r} \left(\bar{R}_t\right)^{1-\rho^r} \exp\left[\epsilon_t^r\right], \tag{6}$$

where the parameter ρ^r reflects the degree of interest rate smoothing, while ϵ_t^r represents a monetary policy shock. The central bank's target nominal interest rate, $\bar{R}_t$ depends the deviation of output from the level consistent with current technologies and "normal" (steady-state) utilization of capital and labor ($\tilde{X}^{pf}$, the "production function" output gap) Consumer price inflation also enters the target. The target equation is:

$$\bar{R}_t = \left(\tilde{X}_t^{pf}\right)^{r^y} \left(\frac{\Pi_t^c}{\Pi_*^c}\right)^{r^\pi} R_*. \tag{7}$$

In equation (7), R_* denotes the economy's steady-state nominal interest rate, and ϕ^y and ϕ^π denote the weights in the feedback rule. Consumer price inflation, Π_t^c, is the weighted average of inflation in the nominal prices of the goods produced in each sector, $\Pi_t^{p,cbi}$ and $\Pi_t^{p,kb}$:

$$\Pi_t^c = (\Pi_t^{p,cbi})^{1-w_{cd}} (\Pi_t^{p,kb})^{w_{cd}}. \tag{8}$$

The parameter w^{cd} is the share of the durable goods in nominal consumption expenditures.

The model also includes a long-term interest rate (RL_t), which is governed by the expectations hypothesis subject to an exogenous term premia shock:

$$RL_t = \mathcal{E}_t \left[\Pi_{\tau=0}^N R_\tau\right] \cdot \Upsilon_t. \tag{9}$$

where Υ is the exogenous term premium, governed by

$$Ln\left(\Upsilon_t\right) = \left(1 - \rho^\Upsilon\right) Ln\left(\Upsilon_*\right) + \rho^\Upsilon Ln\left(\Upsilon_{t-1}\right) + \epsilon_t^\Upsilon. \tag{10}$$

In this version of EDO, the long-term interest rate plays no allocative role; nonetheless, the term structure contains information on economic developments useful for forecasting (e.g., Edge, Kiley, and Laforte (2010)) and hence RL is included in the model and its estimation.

4.7 Summary of Model Specification

Our brief presentation of the model highlights several points. First, although our model considers production and expenditure decisions in a bit more detail, it shares many similar features with other DSGE models in the literature, such as imperfect competition, nominal price and wage rigidities, and real frictions like adjustment costs and habit-persistence. The rich specification of structural shocks (to aggregate and investment-specific productivity, aggregate and sector-specific risk premiums, and mark-ups) and adjustment costs allows our model to be brought to the data with some chance of finding empirical validation.

Within EDO, fluctuations in all economic variables are driven by thirteen structural shocks. It is most convenient to summarize these shocks into five broad categories:

- Permanent technology shocks: This category consists of shocks to aggregate and investment-specific (or fast-growing sector) technology.

- A labor supply shock: This shock affects the willingness of to supply labor. As was apparent in our earlier description of the unemployment rate and in the presentation of the structural drivers below, this shock captures very persistent movements in unemployment that the model judges are not indicative of wage pressures. While EDO labels such movements labor supply shocks, an alternative interpretation would descrbie these as movements in unemployment that reflect persistent strucutral features not otherwise captured by the model.

- Financial, or intertemporal, shocks: This category consists of shocks to risk premia. In EDO, variation in risk premia – both the premium households' receive relative to the federal funds rate on nominal bond holdings and the additional variation in discount rates applied to the investment decisions of capital intermediaries – are purely exogenous. Nonetheless, the specification captures aspects of related models with more explicit financial sectors (e.g., Bernanke, Gertler, and Gilchrist (1999)), as we discuss in our presentation of the model's properties below.

- Markup shocks: This category includes the price and wage markup shocks.

- Other demand shocks: This category includes the shock to autonomous demand and a monetary policy shock.

5 Estimation: Data and Properties

5.1 Data

The empirical implementation of the model takes a log-linear approximation to the first-order conditions and constraints that describe the economy's equilibrium, casts this resulting system in its state-space representation for the set of (in our case 13) observable variables, uses the Kalman filter to evaluate the likelihood of the observed variables, and forms the posterior distribution of the parameters of interest by combining the likelihood function with a joint density characterizing some prior beliefs. Since we do not have a closed-form solution of the posterior, we rely on Markov-Chain Monte Carlo (MCMC) methods.

The model is estimated using 13 data series over the sample period from 1984:Q4 to 2011:Q4. The series are:

1. The civilian unemployment rate (U);
2. The growth rate of real gross domestic product (ΔGDP);
3. The growth rate of real consumption expenditure on non-durables and services (ΔC);
4. The growth rate of real consumption expenditure on durables (ΔCD);
5. The growth rate of real residential investment expenditure (ΔRes);
6. The growth rate of real business investment expenditure (ΔI);

7. Consumer price inflation, as measured by the growth rate of the Personal Consumption Expenditure (PCE) price index ($\Delta P_{C,total}$);
8. Consumer price inflation, as measured by the growth rate of the PCE price index excluding food and energy prices ($\Delta P_{C,core}$);
9. Inflation for consumer durable goods, as measured by the growth rate of the PCE price index for durable goods (ΔP_{cd});
10. Hours, which equals hours of all persons in the non-farm business sector from the Bureau of Labor Statistics (H);[10]
11. The growth rate of real wages, as given by compensation per hour in the non-farm business sector from the Bureau of Labor Statistics divided by the GDP price index (ΔRW);
12. The federal funds rate (R).
13. The yield on the 2-yr. U.S. Treasury security (RL).

Our implementation adds measurement error processes to the likelihood implied by the model for all of the observed series used in estimation except the short-term nominal interest rate series.

5.2 Variance Decompositions and impulse responses

We provide detailed variance decompositions and impulse response in Chung, Kiley, and Laforte (2011), and only highlight the key results here.

Volatility in aggregate GDP growth is accounted for primarily by the technology shocks in each sector, although the economy-wide risk premium shock contributes non-negligibly at short horizons.

Volatility in the unemployment rate is accounted for primarily by the economy-wide risk premium and business investment risk premium shocks at horizons between one and sixteen quarters. Technology shocks in each sector contribute very little, while the labor supply shock contributes quite a bit a low frequencies. The large role for risk premia shocks in the forecast error decomposition at business cycle horizons illustrates the importance of this type of "demand" shock for volatility in the labor market. This result is notable, as the unemployment rate is the series most like a "gap" variable in the model – that is, the unemployment rate shows persistent cyclical fluctuations about its long-run value.

Volatility in core inflation is accounted for primarily by the markup shocks.

Volatility in the federal funds rate is accounted for primarily by the economywide risk premium (except in the very near term, when the monetary policy shock is important).

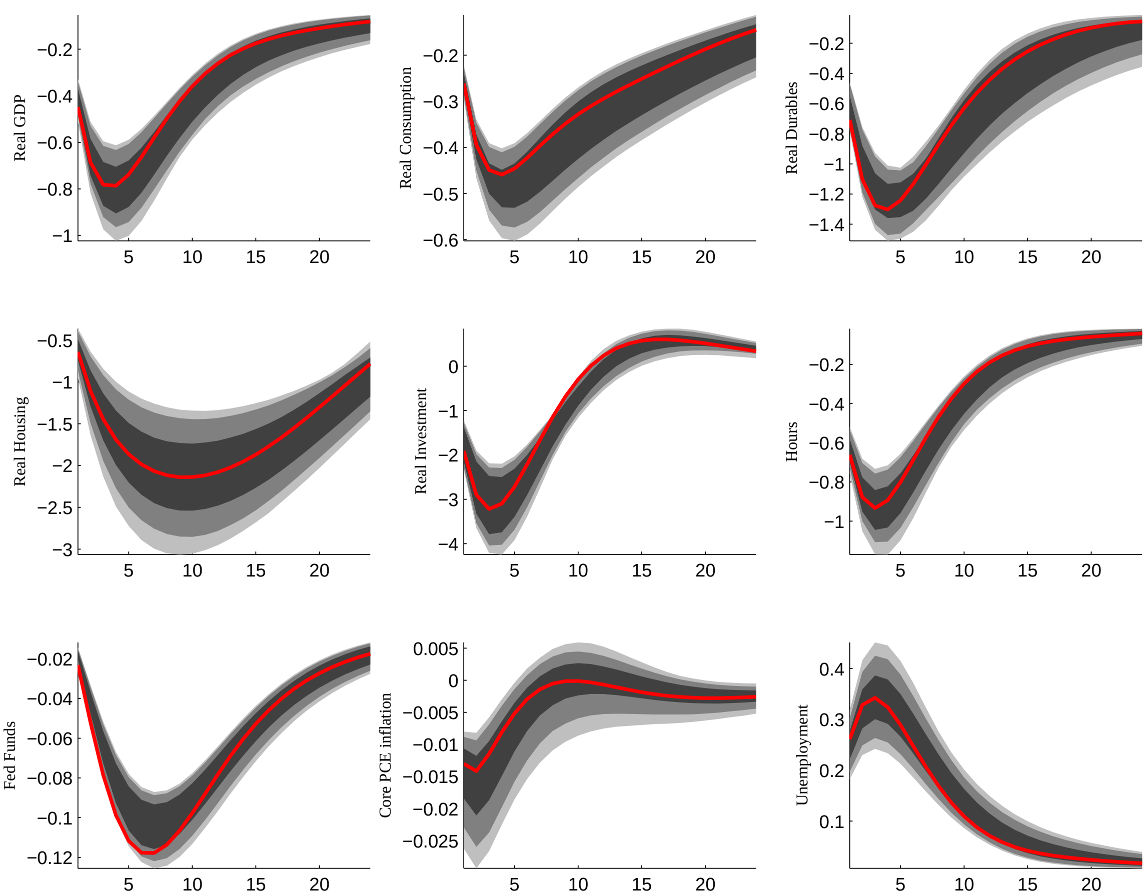
Volatility in expenditures on consumer non-durables and non-housing services is, in the near horizon, accounted for predominantly by economy-wide risk-premia shocks. In the far horizon, volatility is accounted for primarily by capital-specific and economy-wide technology shocks.

Volatilities in expenditures on consumer durables, residential investment, and non-residential investment are, in the near horizon, accounted for predominantly by their own sector

[10]We remove a low-frequency trend from hours. We first pad the historical series by appending 40 quarterly observations which approach the most recent 40-quarter moving average of the data at a rate of 0.05 percent per quarter. We then extract a trend from this padded series via the Hodrick-Prescott filter with a smoothing parameter of 6400; our model is not designed to capture low frequency trends in population growth or labor force participation.

specific risk-premium shocks. At farther horizons, their volatilities are accounted for by technology shocks.

Figure 11: Impulse Response to a One Standard Deviation Shock to the Aggregate Risk Premium.

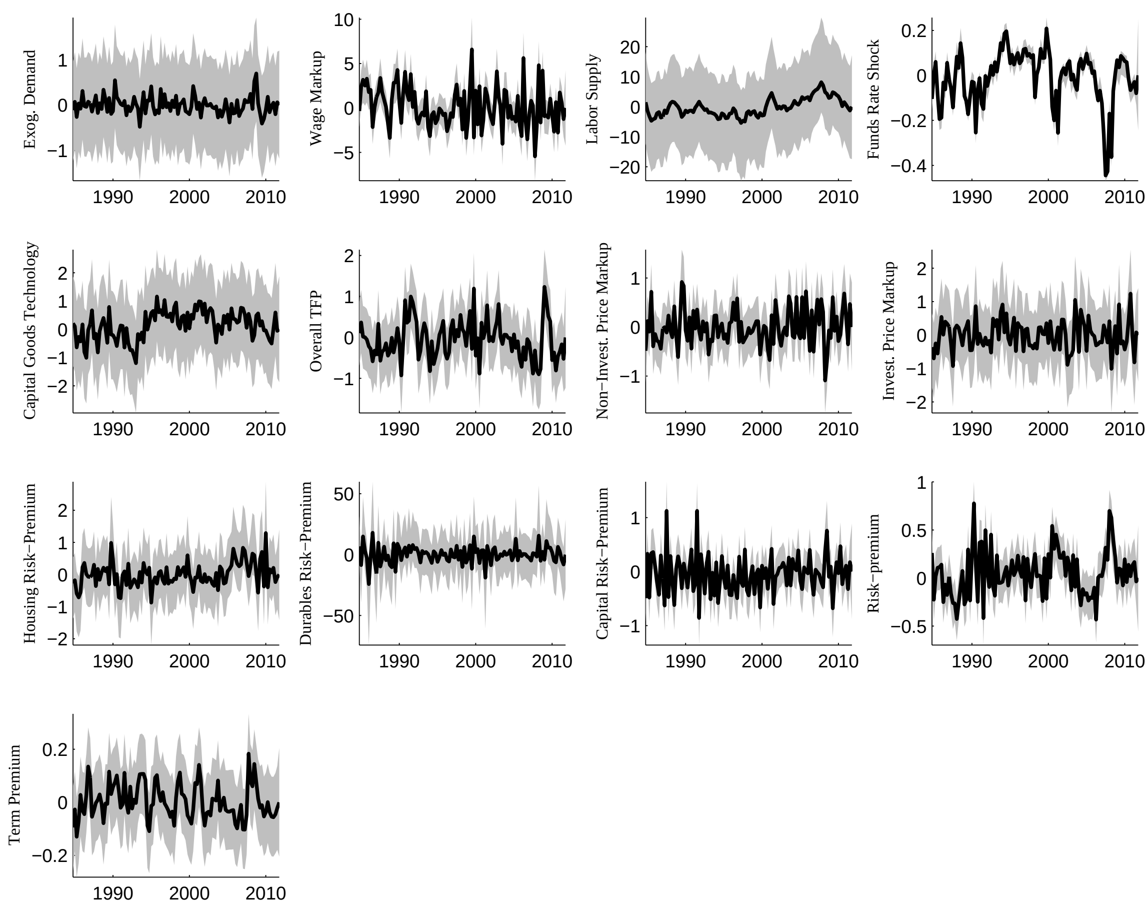


With regard to impulse responses, we highlight the responses to the most important shock, the aggregate risk premium, in figure 11. As we noted, this shock looks like a traditional demand shock, with an increase in the risk premium lowering real GDP, hours worked, and inflation; monetary policy offsets these negative effects somewhat by becoming more accommodative. As for responses to other disturbances, the impulse responses to a monetary policy innovation captures the conventional wisdom regarding the effects of such shocks. In particular, both household and business expenditures on durables (consumer durables, residential investment, and nonresidential investment) respond strongly (and with a hump-shape) to a contractionary policy shock, with more muted responses by nondurables and services consumption; each measure of inflation responds gradually, albeit more quickly than in some analyses based on vector autoregressions (VARs).[11]

Shocks to sectoral risk premia principally depress spending in the associated category of expenditure (e.g., an increase in the residential risk premium lowers residential investment), with offsetting positive effects on other spending (which is "crowded in").

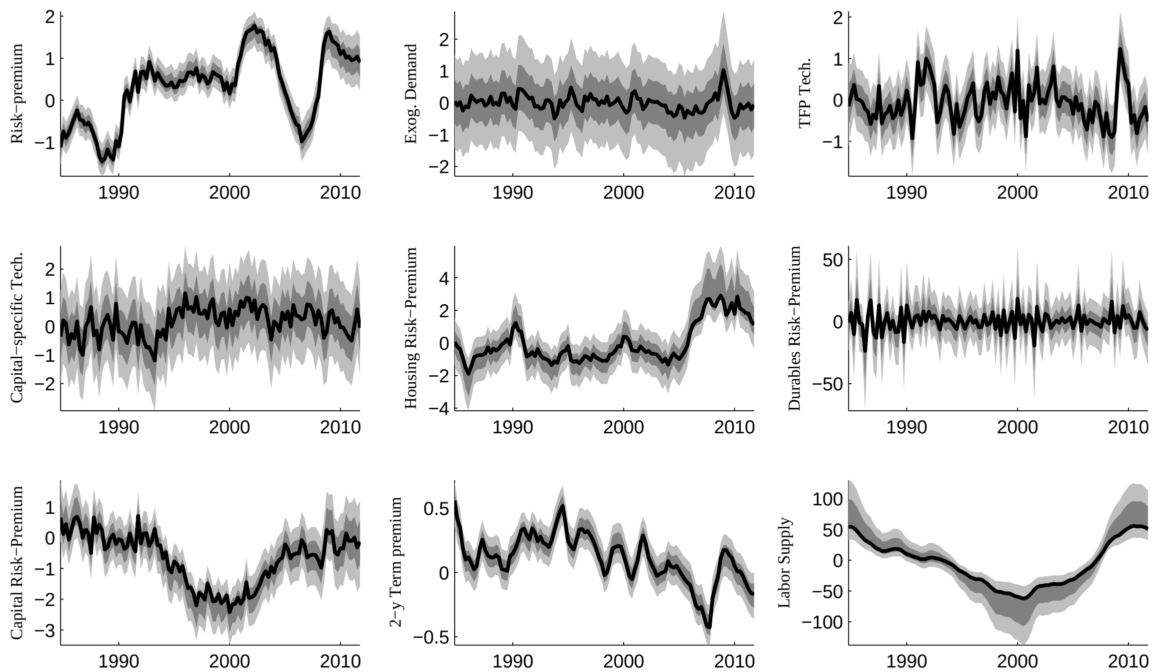
Following an economy-wide technology shock, output rises gradually to its long-run level; hours respond relatively little to the shock (in comparison to, for example, output), reflecting both the influence of stick prices and wages and the offsetting income and substitution effects of such a shock on households willingness to supply labor.

Figure 12: Innovations to Exogenous Processes



[11] This difference between VAR-based and DSGE-model based impulse responses has been highlighted elsewhere – for example, in the survey of Boivin, Kiley, and Mishkin (2010).

Figure 13: Exogenous Drivers



5.3 Estimates of Latent Variable Paths

Figures 12 and 13 report modal estimates of the model's structural shocks and the persistent exogenous fundamentals (i.e., risk premia and autonomous demand). These series have recognizable patterns for those familiar with U.S. economic fluctuations. For example, the risk premia jump at the end of the sample, reflecting the financial crisis and the model's identification of risk premia, both economy-wide and for housing, as key drivers.

Of course, these stories from a glance at the exogenous drivers yield applications for alternative versions of the EDO model and future model enhancements. For example, the exogenous risk premia can easily be made to have an endogenous component following the approach of Bernanke, Gertler, and Gilchrist (1999) (and indeed we have considered models of that type). At this point we view incorporation of such mechanisms in our baseline approach as premature, pending ongoing research on financial frictions, banking, and intermediation in dynamic general equilibrium models. Nonetheless, the EDO model captured the key financial disturbances during the last several years in its current specification, and examining the endogenous factors that explain these developments will be a topic of further study.

6 Appenix: Additional Rules Simulations

In this section, we present simulation results for six alternative rules, given the EDO baseline forecast.

$$
\begin{array}{cc}
\text{(Inertial Taylor 93)} & R_t = 0.85R_{t-1} + 0.15(1.5\bar{\pi}_t + 0.5GAP_t) \\
\text{(Inertial Taylor 99)} & R_t = 0.85R_{t-1} + 0.15(1.5\bar{\pi}_t + 1GAP_t) \\
\text{(Hours rule)} & R_t = 0.75R_{t-1} + 0.25(2\bar{\pi}_t + 0.4Hours_t) \\
\text{(First Diff Rule)} & R_t = R_{t-1} + 0.5(\pi_{t+3|t} + \Delta^4 GAP_{t+3|t}) \\
\text{(Outcome-based Rule)} & R_t = 1.20R_{t-1} + 0.329\bar{\pi}_t + 0.695GAP_t - 0.517GAP_{t-1} \\
\text{(Nominal Income Target)} & R_t = 0.75R_{t-1} + 0.25NOMGAP_t \\
\text{(Price Level Target)} & R_t = 0.75R_{t-1} + 0.25(2PLGAP_t)
\end{array} \tag{11}
$$

where all variables are expressed in log-deviations from steady-state, and interest rates are annualized.

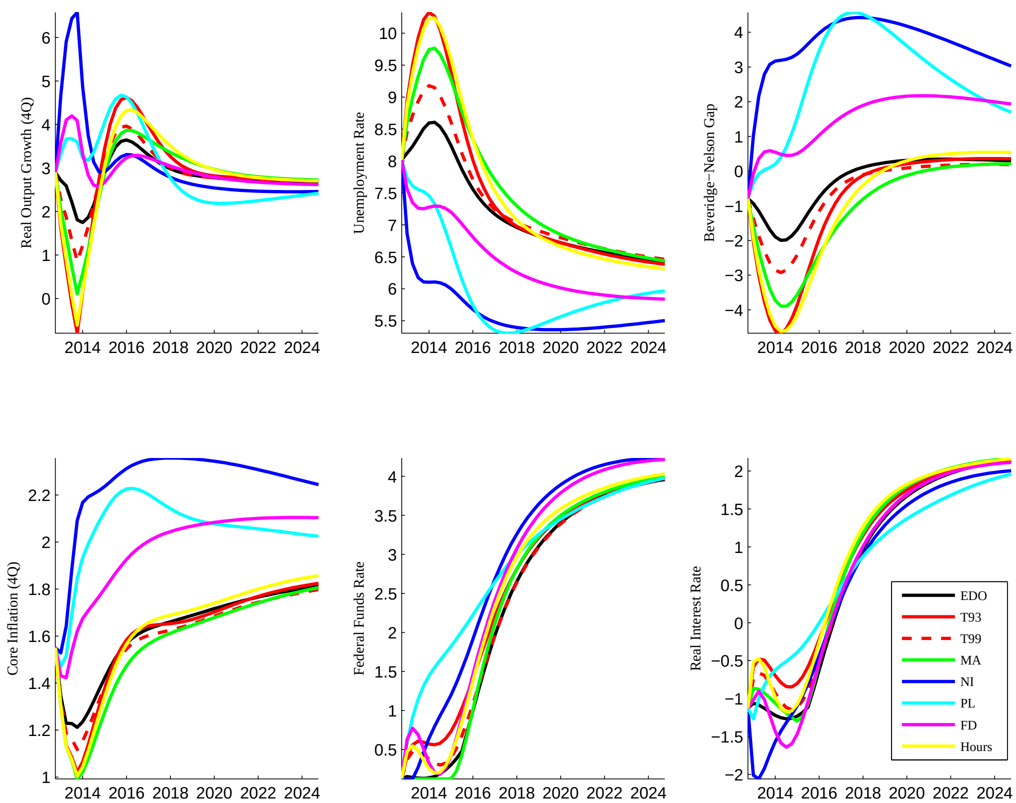


Figure 14: Simulations with alternative policy rules (EDO baseline initial conditions)

The Taylor-type rules (the two Taylor rules, the hours rule and the outcome-based rule) all lift off earlier than does the native rule, and, thereafter, rise more steeply. Given the consistently higher real interest rate path implied by these rules, output falls well below baseline by the end of 2013, with the hours rule and Taylor 93 inducing particularly weak real activity. The effects on inflation, however, are muted and fairly transient. Under all Taylor-type rules, core inflation has largely converged back to baseline by end of 2017.

References

[Bernanke, Gertler, and Gilchrist (1999)] Bernanke, B., M. Gertler, and S. Gilchrist. 1999. The financial accelerator in a quantitative business cycle framework, In: John B. Taylor and Michael Woodford, Editor(s), Handbook of Macroeconomics, Elsevier, 1999, Volume 1, Part 3, Pages 1341-1393.

[Beveridge and Nelson (1981)] Beveridge, S. and C.R. Nelson. 1981. A new approach to the decomposition of economic time series into permanent and transitory components with particular attention to measurement of the business cycle, Journal of Monetary Economics vol. 7, Pages 151-174.

[Boivin et al. (2010)] Boivin, J., M. Kiley, and F.S. Mishkin. 2010. How Has the Monetary Transmission Mechanism Evolved Over Time? In B. Friedman and M. Woodford, eds., The Handbook of Monetary Economics, Elsevier.

[Chung et al. (2011)] Chung, Hess, J.P. Laforte, David L. Reifschneider, and John C. Williams. 2010. Have We Underestimated the Likelihood and Severity of Zero Lower Bound Events. Federal Reserve Bank of San Francisco Working Paper 2011-01 http://www.frbsf.org/publications/economics/papers/2011/wp11-01bk.pdf

[Edge, Kiley, and Laforte (2008)] Edge, R., Kiley, M., Laforte, J.P., 2008. Natural rate measures in an estimated DSGE model of the U.S. economy. Journal of Economic Dynamics and Control vol. 32(8), Pages 2512-2535.

[Edge, Kiley, and Laforte (2010)] Edge, R., Kiley, M., Laforte, J.P., 2010. A comparison of forecast performance between Federal Reserve staff forecasts, simple reduced-form models, and a DSGE model. Journal of Applied Econometrics vol. 25(4), Pages 720-754.

[Fisher (2006)] Fisher, Jonas D. M., 2006. The Dynamic Effects of Neutral and Investment-Specific Technology Shocks. Journal of Political Economy, University of Chicago Press, vol. 114(3), Pages 413-451.

[Gali (2011)] Gali, Jordi, 2011. The Return Of The Wage Phillips Curve. Journal of the European Economic Association vol. 9(3), pages 436-461.

[Hall (2010)] Hall, Robert E., 2010. Why Does the Economy Fall to Pieces after a Financial Crisis? Journal of Economic Perspectives vol. 24(4), Pages 3-20. http://www.aeaweb.org/articles.php?doi=10.1257/jep.24.4.3

[Kiley (2007)] Kiley, M., 2007. A Quantitative Comparison of Sticky-Price and Sticky-Information Models of Price Setting. Journal of Money, Credit, and Banking 39, Pages 101-125.

[Kiley (2010a)] Kiley, M., 2010a. Habit Persistence, Non-separability between Consumption and Leisure, or Rule-of-Thumb Consumers: Which Accounts for the Predictability of Consumption Growth? The Review of Economics and Statistics vol. 92(3), Pages 679-683.

[Kiley (2010b)] Kiley, M., 2010b. Output Gaps. Federal Reserve Board Finance and Economics Discussion Series (FEDS), 2010-27.

[Kydland and Prescott (1982)] Kydland, Finn and Prescott, Edward. 1982. Time-to-build and Aggregate Fluctuations. Econometrica vol. 50(6), Pages 1345 - 1370.

[Laforte (2007)] Laforte, J., 2007. Pricing Models: A Bayesian DSGE Approach to the U.S. Economy. Journal of Money, Credit, and Banking vol. 39, Pages 127-54.

[Smets and Wouters (2007)] Smets, F., Wouters, R., 2007. Shocks and Frictions in the US Busines Cycles: A Bayesian DSGE Approach. American Economic Review, American Economic Association, vol. 97(3), Pages 586-606.

[Wieland and Wouters (2010)] Wieland, Volker and Wolters, Maik H, 2010. The Diversity of Forecasts from Macroeconomic Models of the U.S. Economy. CEPR Discussion Papers 7870, C.E.P.R. Discussion Papers.

Detailed Philadelphia (PRISM) Forecast Overview

November 2012

Keith Sill

Forecast Summary

The FRB Philadelphia DSGE model denoted PRISM, projects that real GDP growth will run at a fairly strong pace over the forecast horizon with real output growth peaking at about 5 percent in the first quarter of 2014. Inflation is projected to be contained at 1.75 percent or below through 2015, even with significantly above-trend output growth. For this forecast round, we have implemented the assumption that the forecasted federal funds rate is pinned down by current futures market projections through mid-2015. The funds rate is unconstrained beginning in 2015Q3, and rises to 1.5 percent in 2015Q4. Many of the model's variables continue to be well below their steady-state values. In particular, consumption, investment, and the capital stock are low relative to steady state, and absent any shocks, the model would predict a rapid recovery. These state variables have been below steady state since the end of the recession. The relatively slow recovery to date and the low inflation that has recently characterized U.S. economic activity require the presence of shocks to offset the strength of the model's internal propagation channels.

The Current Forecast and Shock Identification

The PRISM model is an estimated New Keynesian DSGE model with sticky wages, sticky prices, investment adjustment costs, and habit persistence. The model is similar to the Smets & Wouters 2007 model and is described more fully in Schorfheide, Sill, and Kryshko 2010. Unlike in that paper though, we estimate PRISM directly on core PCE inflation rather than projecting core inflation as a non-modeled variable. Details on the model and its estimation are available in a Technical Appendix that was distributed for the June 2011 FOMC meeting or is available on request.

The current forecasts for real GDP growth, core PCE inflation, and the federal funds rate are shown in Figures 1a-1c along with the 68 percent probability coverage intervals. The forecast uses data through 2012Q3 supplemented by a nowcast for real GDP growth, core PCE inflation, and the federal funds rate for 2012Q4. The model takes 2012Q4 output growth of 1.75 percent as given and the projection begins with 2013Q1. PRISM continues to anticipate a strong rebound in real GDP growth, which rises to 4.9 percent by the end of 2013. Output growth begins to taper off in mid-2014, falling to a 3.6 percent pace in 2015Q4. While output growth is fairly robust, core PCE inflation stays contained at about 1.75 percent through the forecast horizon. Based on the 68 percent coverage interval, the model sees a minimal chance of deflation or recession (measured as negative quarters of real GDP growth) over the next 3 years. The federal funds rate is constrained near the zero bound through mid-2015. Thereafter, the model dynamics take over and the funds rate rises to 1.5 percent in 2015Q4.

The key factors driving the projection are shown in the forecast shock decompositions (shown in Figures 2a-2e) and the smoothed estimates of the model's primary shocks (shown in Figure 3, where they are normalized by standard deviation). The primary shocks driving above-trend real output growth over the next 3 years are financial shocks in the form of discount factor shocks (labeled Fin), marginal efficiency of investment shocks (labeled MEI), and labor supply shocks (labeled Labor). Over the course of the recession and recovery PRISM estimated a sequence of large positive shocks to leisure (negative shocks to labor supply) that have a persistent effect on hours worked and so pushed hours well below steady state. As these shocks unwind hours worked rebounds strongly over the forecast horizon and so leads to higher output growth.

The model continues to estimate a sequence of largely negative discount factor shocks since 2008. All else equal, these shocks push down current consumption and push up investment, with the effect being very persistent. Consequently, the de-trended level of consumption (nondurables + services) remains well below the model's estimated steady state at this point. As these shocks wane over the projection period, consumption growth picks up to about a 3 percent annual pace over most of the next three years. The negative discount factor shocks worked to strengthen investment in 2010 and 2011, but investment was pushed well below steady state by adverse MEI shocks over 2007 to 2009. Negative investment shocks are the major factor behind weak investment growth over the last three quarters of 2012 as well. As these shocks wane, they make a strong positive contribution to investment growth over the next 3 years (and MEI shocks are a negative contributor to consumption growth over the forecast horizon). Note though that the unwinding of the discount factor shocks that contributed positively to investment growth over 2009-2011 leads to a downward pull on investment growth over the next three years. On balance, investment growth runs at a better than 10 percent pace over the next two years, easing back to about a 6 percent pace by the end of 2015.

The forecast for core PCE inflation is largely a story of upward pressure from the unwinding of labor supply shocks, MEI shocks, and monetary policy shocks being offset by downward pressure from the waning of discount factor shocks. Negative discount factor shocks have a strong and persistent negative effect on marginal cost and inflation in the estimated model. Compared, for example, to a negative MEI shock that lowers real output growth by 1 percent, a negative discount factor shock that lowers real output growth by 1 percent leads to a 3 times larger drop in inflation that is more persistent. The negative discount factor shock leads to capital deepening and higher labor productivity. Consequently, marginal cost and inflation fall. The negative effect of discount factor shocks on inflation is estimated to have been quite significant since the end of 2008. As these shocks unwind over the projection period there is a decreasing, but still substantial, downward effect on inflation over the next three years.

Partly offsetting the downward pressure on inflation from discount factor shocks is the upward pressure coming from labor supply shocks. Labor supply shocks that push down aggregate hours also serve to put upward pressure on the real wage and hence marginal cost. The effect is persistent -- as the labor supply shocks unwind over the forecast horizon they exert a waning upward push to inflation. On balance the effect of these opposing forces is to keep inflation below 2 percent through the forecast horizon.

The Unconditional Forecast

Pinning down the federal funds rate at current market expectations through mid-2015 (using fully anticipated monetary policy shocks) has an impact on the PRISM forecast. Figures 4a-c show the forecast and shock decompositions for the unconditional forecast (ie, a forecast that does not constrain the funds rate path). The forecasted path for real GDP growth is similar to the conditional forecast the next 3 years under a less-accommodative monetary policy. However, the projection for core PCE inflation is above 2 percent through much the forecast horizon even though the federal funds rate begins to rise immediately, reaching a bit above 4 percent by the end of 2015. Thus, the inflation forecast is somewhat stronger if the funds rate is not constrained at the ZLB through mid-2014.

The fact that the forecast with a substantially more accommodative policy has a weaker inflation path and only moderately stronger output path is counter intuitive. It is the case in the PRISM model that an anticipated easing of monetary policy in the future does lead to an immediate jump in current period output and inflation – the economy strengthens with the easier policy. Compared to the unconditional forecast, an anticipated easing of monetary policy leads to a stronger economy and higher inflation today.

Why then the somewhat weaker projection in PRISM under the funds-rate-constrained policy? The reason is that history is locked down in the model. For example, output growth in 2012Q4 is given at 1.75 percent and inflation is 1.5 percent in both the unconditional and conditional forecasts since it is treated as historical data (recall that we use a nowcast for 2012Q4 as data to update the November projection). An easing of future monetary policy, by construction, cannot change 2012Q4 output growth or inflation – or indeed their history. Consequently, the model re-weights shocks so that negative TFP, discount factor, and MEI shocks offset the stimulus from anticipated easier monetary policy in order to keep the history of output growth and inflation unchanged. The persistence of the re-weighted TFP, discount factor, and MEI shocks then shows through as the model projection unfolds. If we were to instead allow the PRISM model variables that map into data observations to immediately adjust in response to an anticipated easing of policy, the economic forecast would look significantly stronger.

As implemented though, leaving the funds rate unconstrained in the forecast shifts the historical shock decomposition to give an expected path for output growth that is similar and inflation that is somewhat higher compared to the conditional forecast. With inflation running at about target and strong output growth, PRISM forecasts that the funds rate should begin rising immediately, reaching 4.2 percent by the end of 2015 -- roughly 270 basis points above the constrained path federal funds rate at that point.

References

Schorfheide, Frank, Keith Sill, and Maxym Kryshko. 2010. “” *International Journal of Forecasting*, 26(2): 348-373.

Smets, Frank, and Rafael Wouters. 2007. “Shocks and Frictions in U.S. Business Cycles: A Bayesian DSGE Approach.” *American Economic Review*, 97(3): 586-606.

Figure 1a

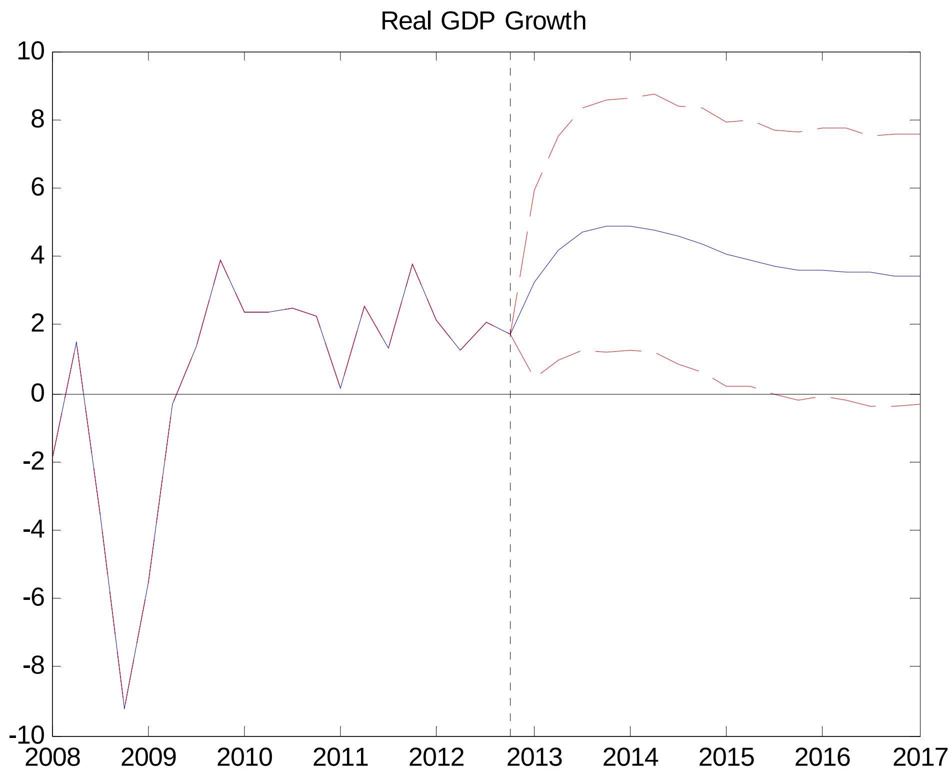

Real GDP Growth
10
8
6
4
2
0
-2
-4
-6
-8
-10
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017

Figure 1b

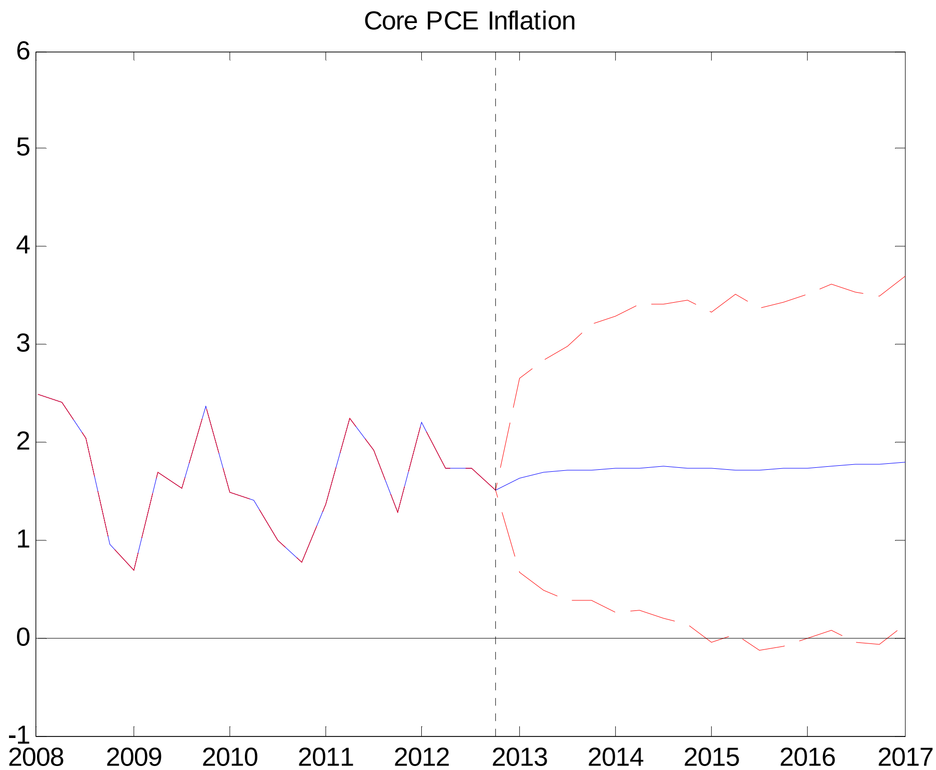

Core PCE Inflation
6
5
4
3
2
1
0
-1
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017

Figure 1c

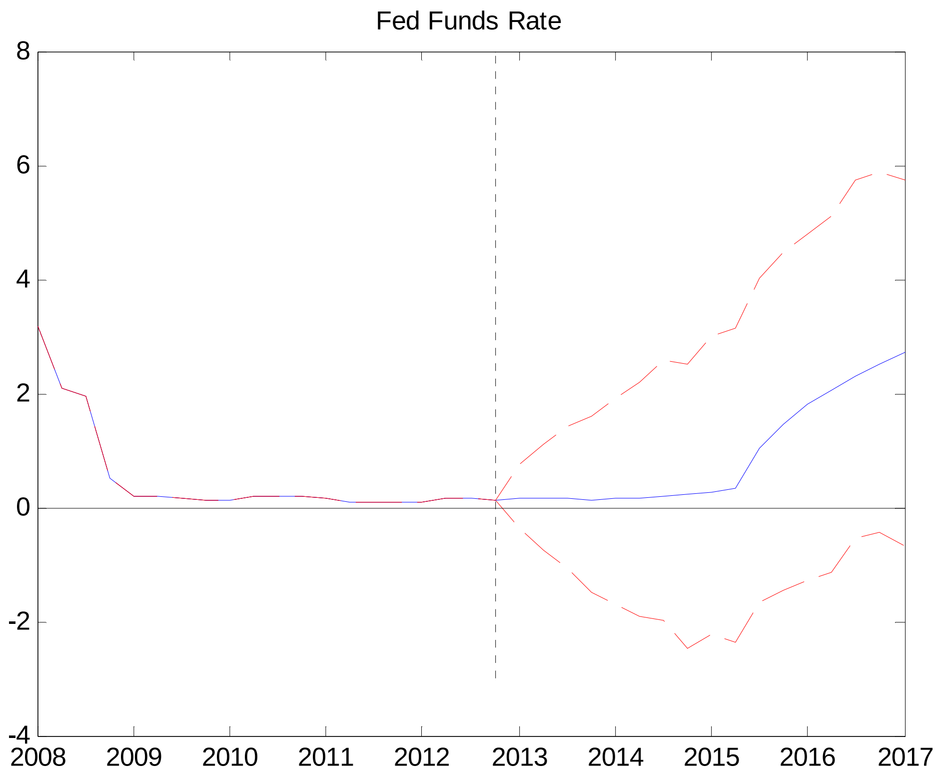
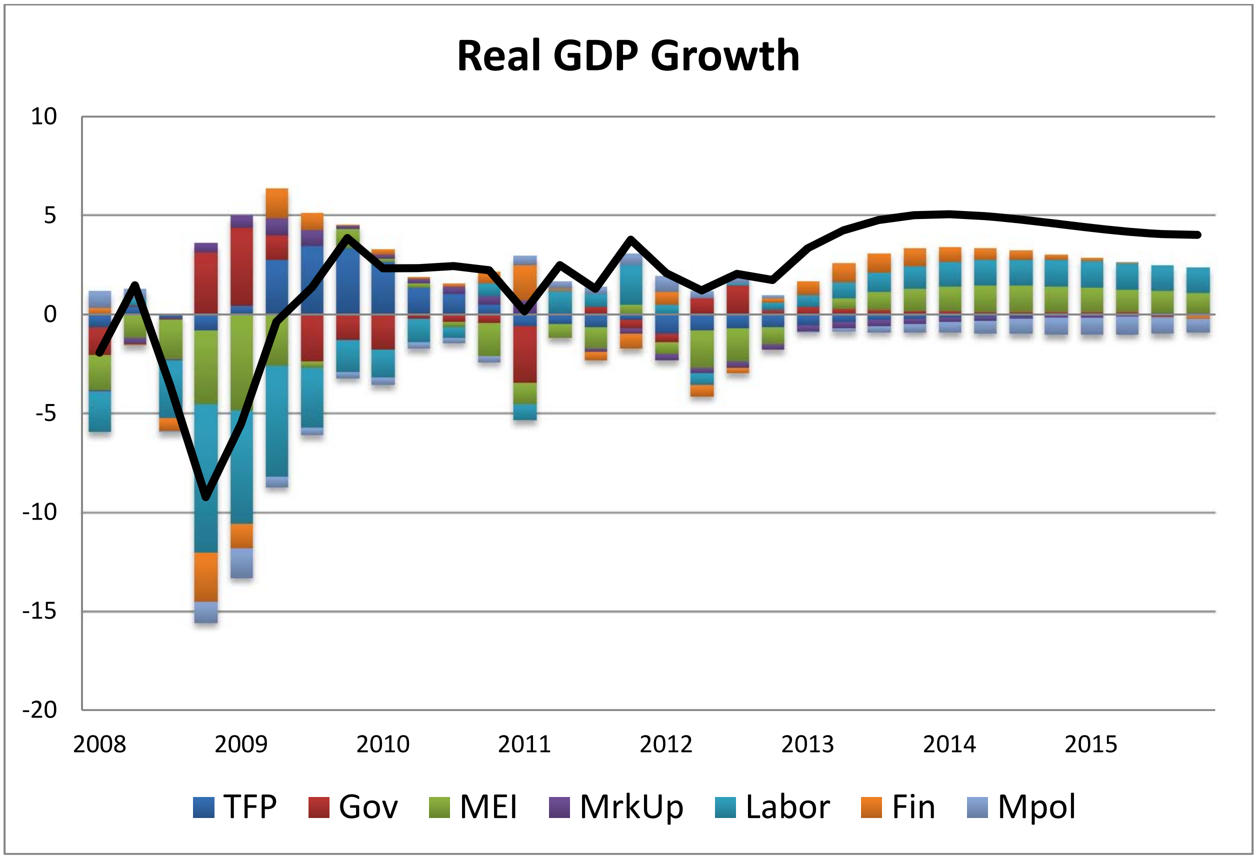

Fed Funds Rate
8
6
4
2
0
-2
-4
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017

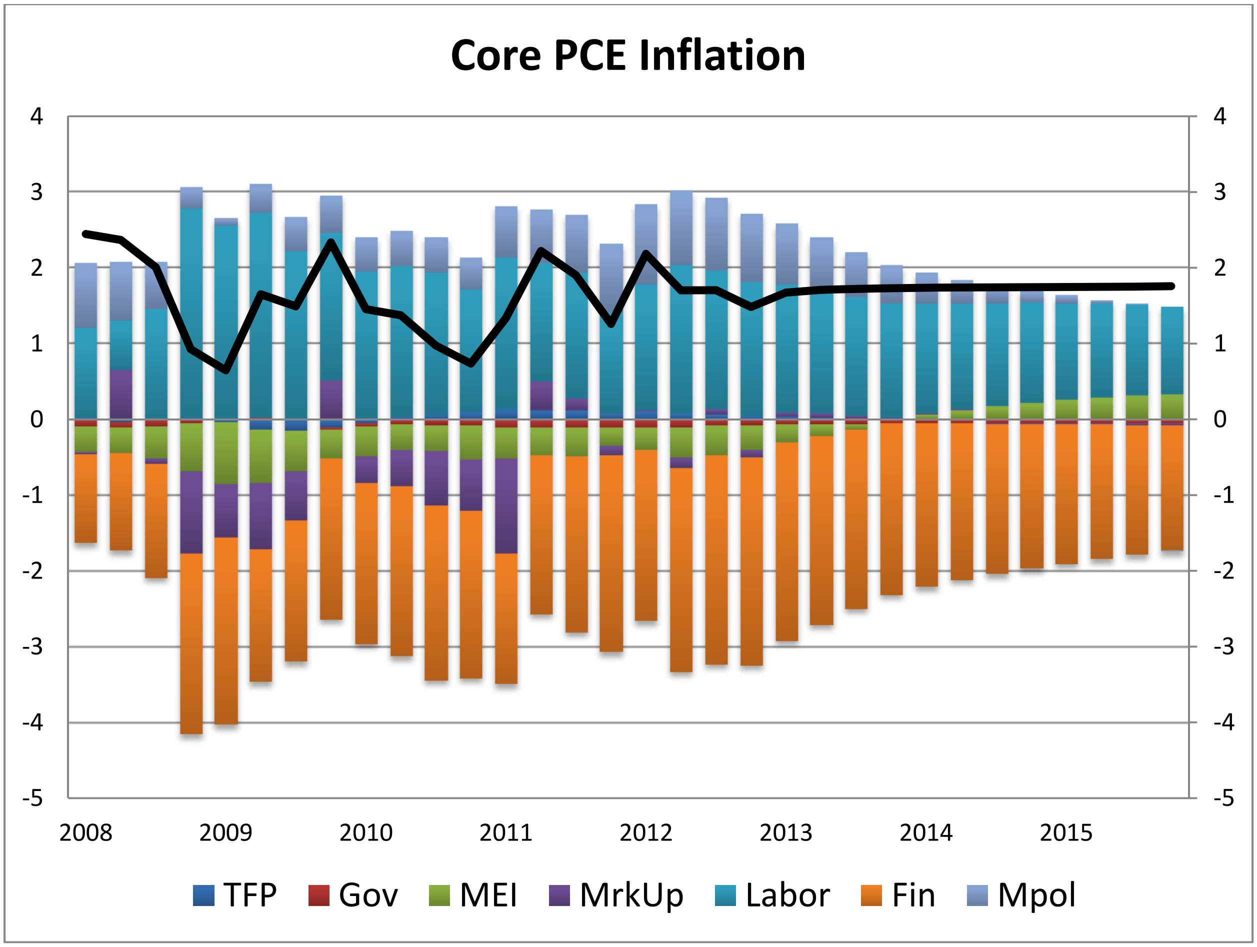
Figure 2a
Conditional Forecast



shocks:

TFP:	Total factor productivity growth shock
Gov:	Government spending shock
MEI:	Marginal efficiency of investment shock
MrkUp:	Price markup shock
Labor:	Labor supply shock
Fin:	Discount factor shock
Mpol:	Monetary policy shock

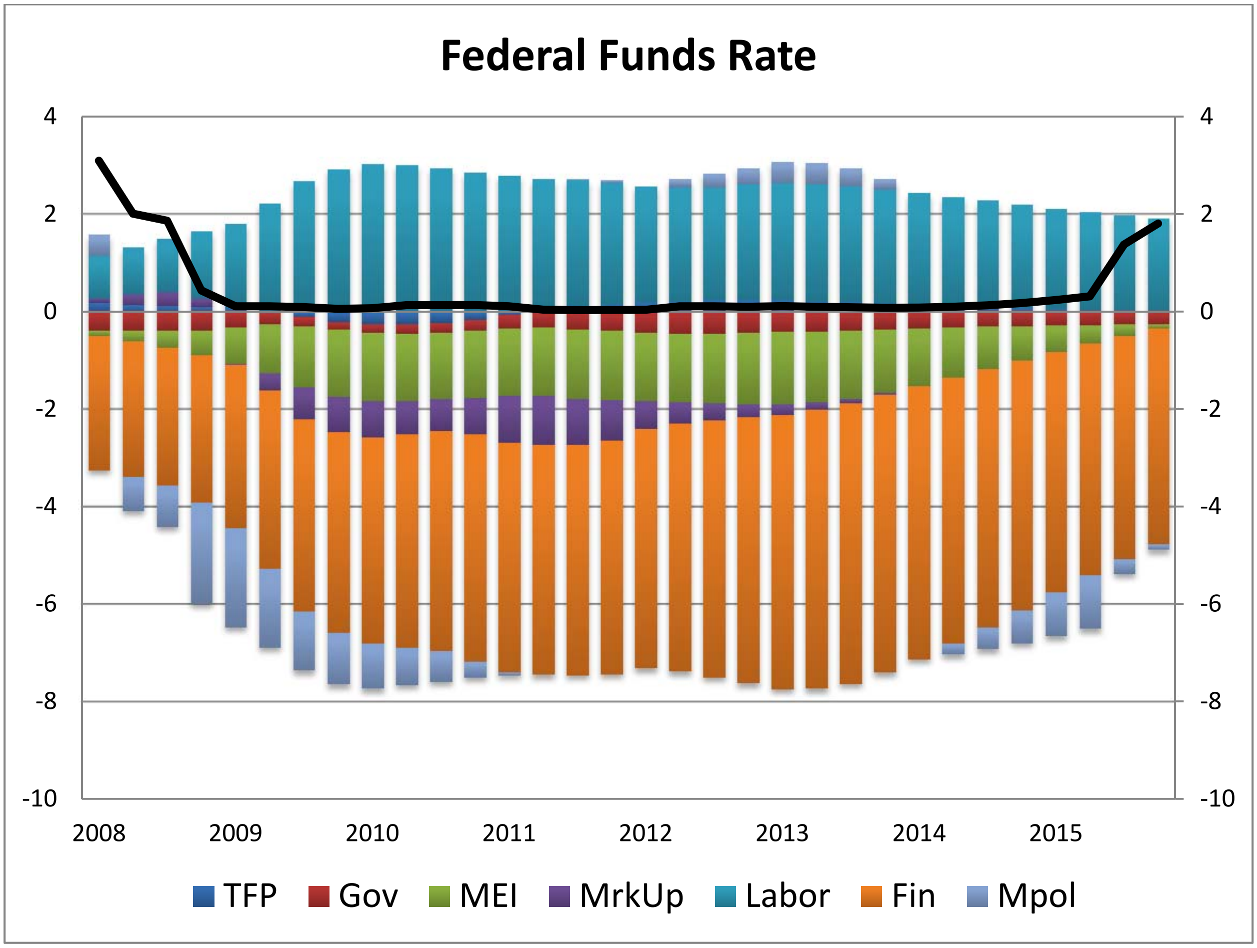
Figure 2b
Conditional Forecast



shocks:

TFP:	Total factor productivity growth shock
Gov:	Government spending shock
MEI:	Marginal efficiency of investment shock
MrkUp:	Price markup shock
Labor:	Labor supply shock
Fin:	Discount factor shock
Mpol:	Monetary policy shock

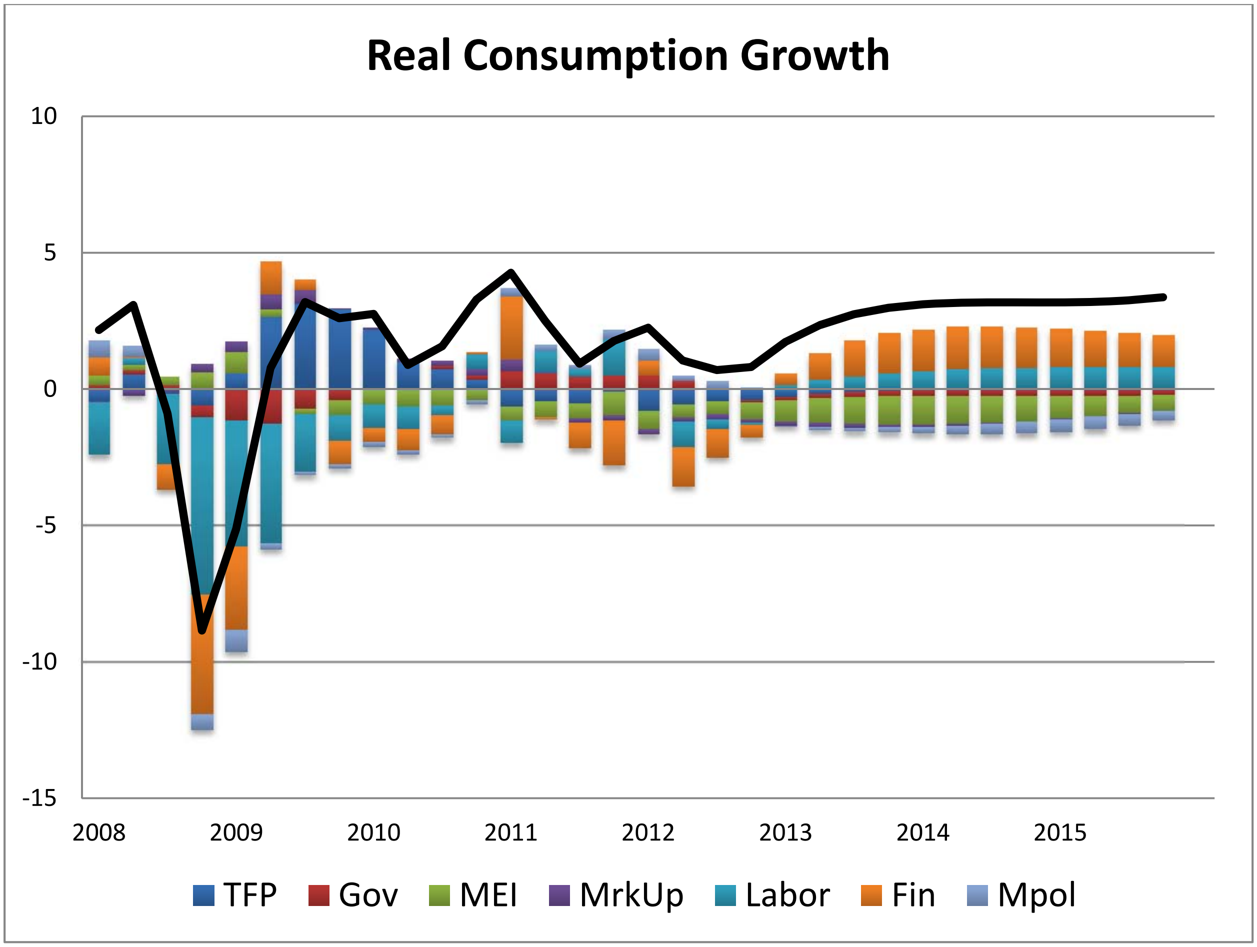
Figure 2c
Conditional Forecast



shocks:

TFP:	Total factor productivity growth shock
Gov:	Government spending shock
MEI:	Marginal efficiency of investment shock
MrkUp:	Price markup shock
Labor:	Labor supply shock
Fin:	Discount factor shock
Mpol:	Monetary policy shock

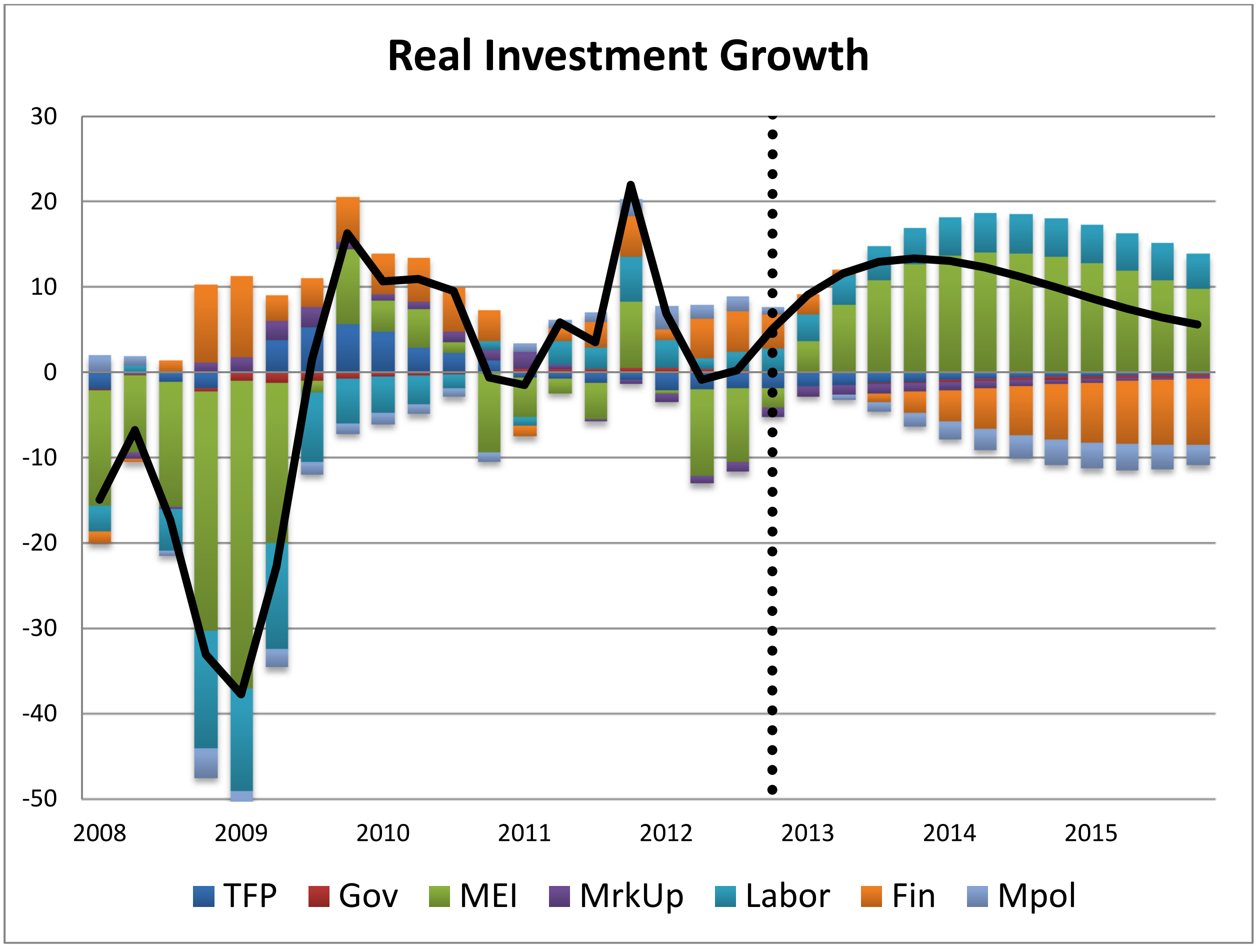
Figure 2d
Conditional Forecast



shocks:

TFP:	Total factor productivity growth shock
Gov:	Government spending shock
MEI:	Marginal efficiency of investment shock
MrkUp:	Price markup shock
Labor:	Labor supply shock
Fin:	Discount factor shock
Mpol:	Monetary policy shock

Figure 2e
Conditional Forecast



shocks:

TFP:	Total factor productivity growth shock
Gov:	Government spending shock
MEI:	Marginal efficiency of investment shock
MrkUp:	Price markup shock
Labor:	Labor supply shock
Fin:	Discount factor shock
Mpol:	Monetary policy shock

Figure 3
Smoothed Shock Estimates for Conditional Forecast Model
(normalized by standard deviation)

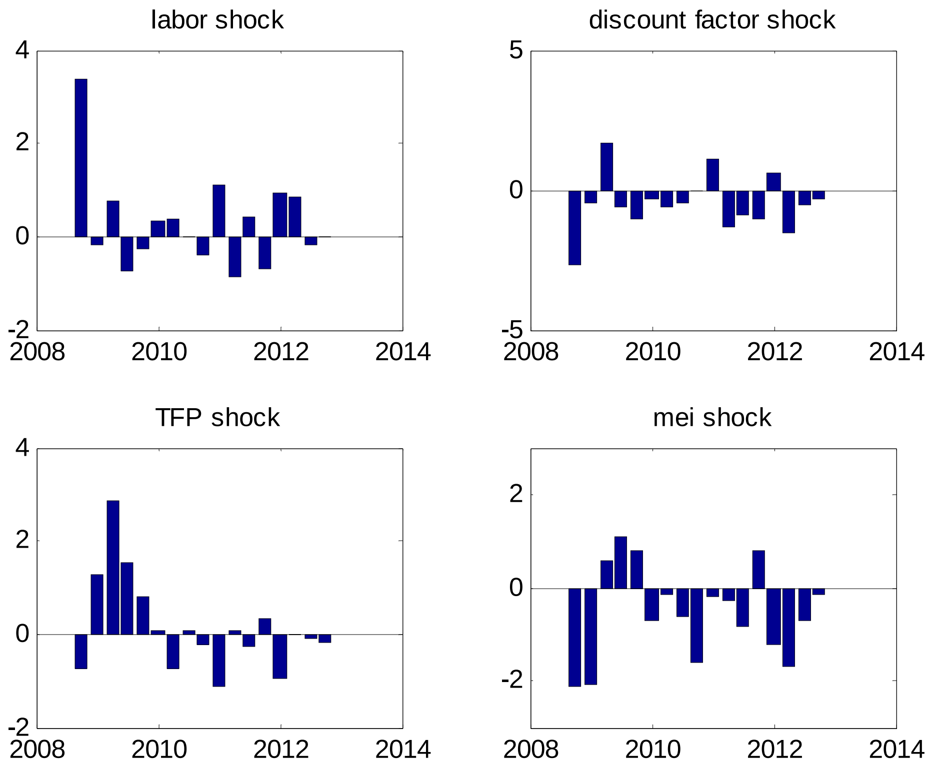
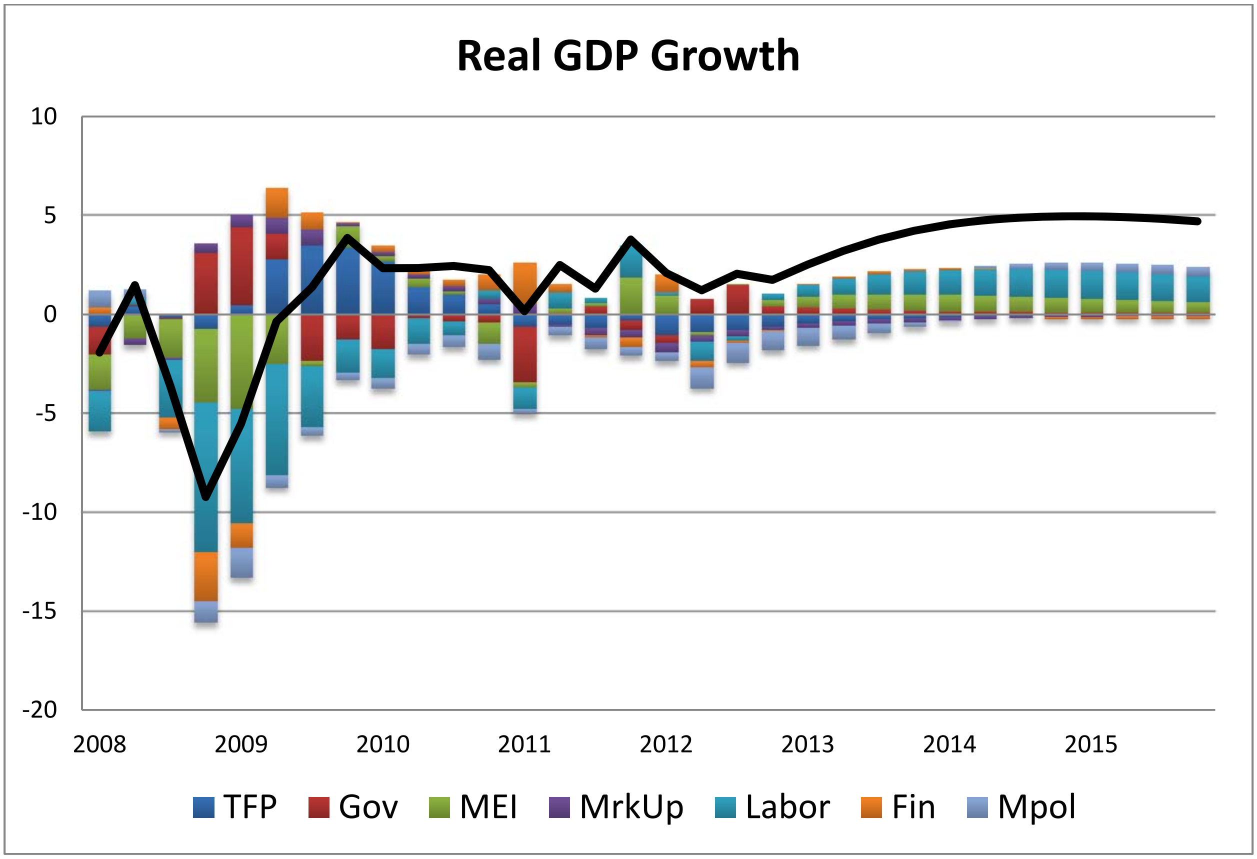


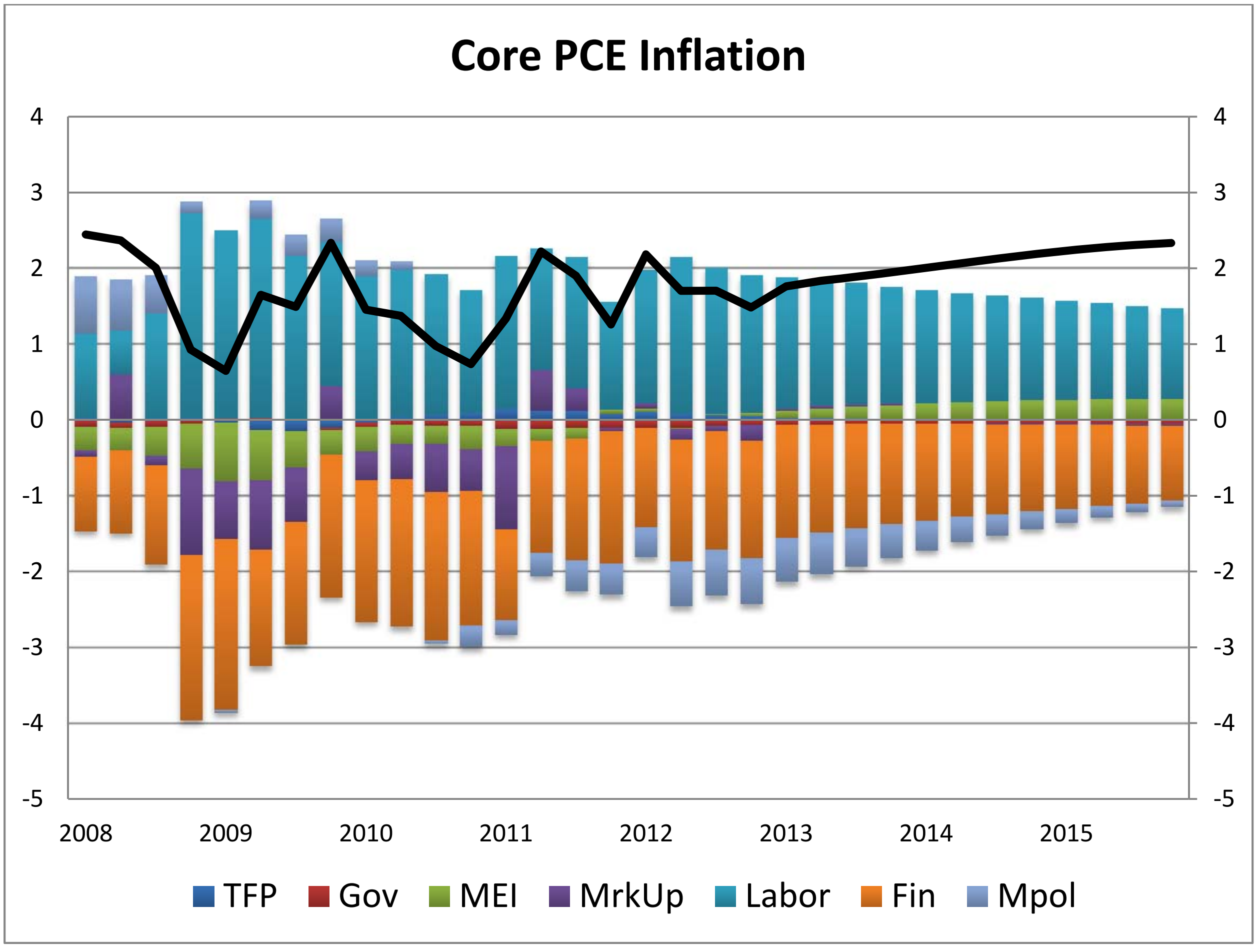
Figure 4a
Unconditional Forecast



shocks:

TFP:	Total factor productivity growth shock
Gov:	Government spending shock
MEI:	Marginal efficiency of investment shock
MrkUp:	Price markup shock
Labor:	Labor supply shock
Fin:	Discount factor shock
Mpol:	Monetary policy shock

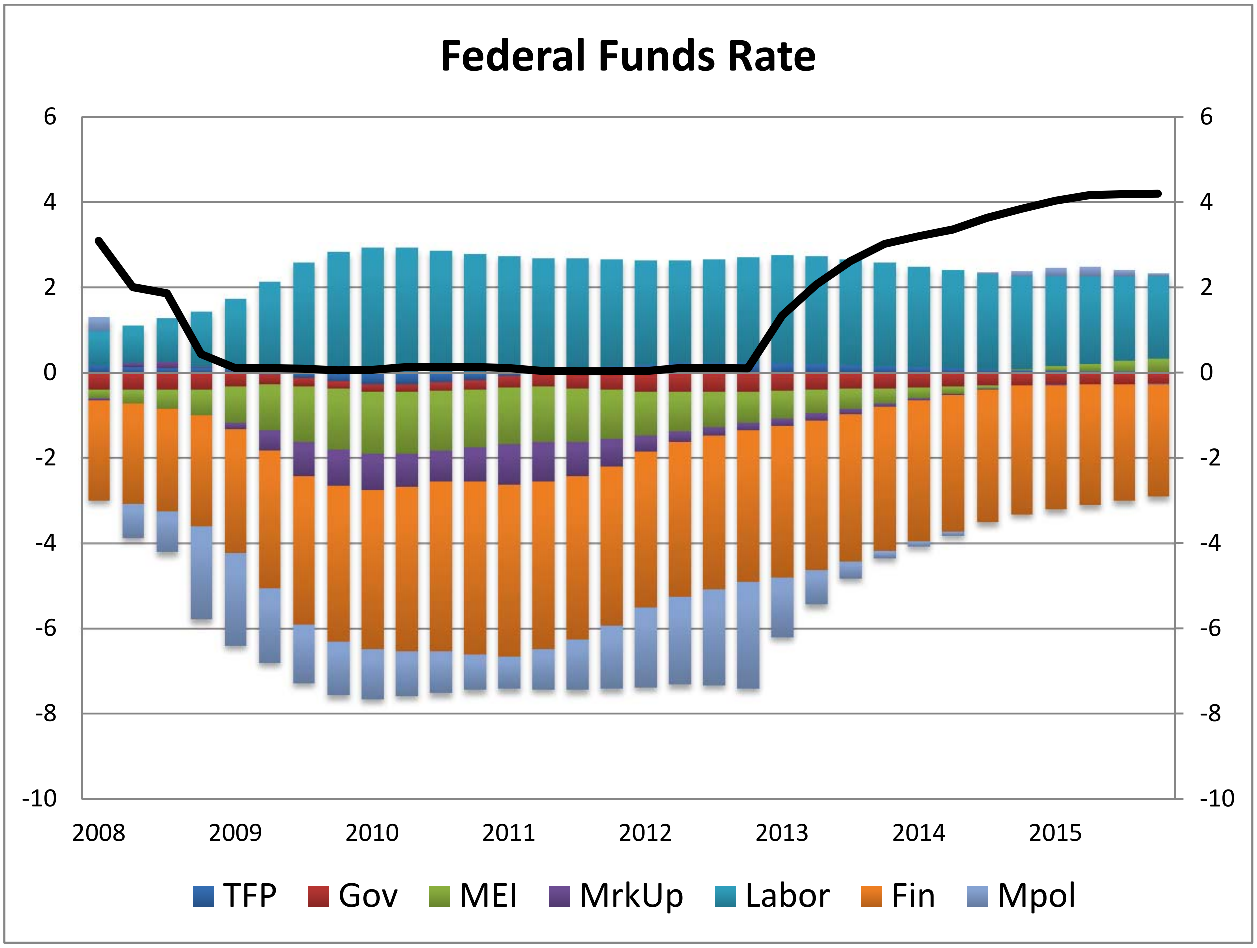
Figure 4b
Unconditional Forecast



shocks:

TFP:	Total factor productivity growth shock
Gov:	Government spending shock
MEI:	Marginal efficiency of investment shock
MrkUp:	Price markup shock
Labor:	Labor supply shock
Fin:	Discount factor shock
Mpol:	Monetary policy shock

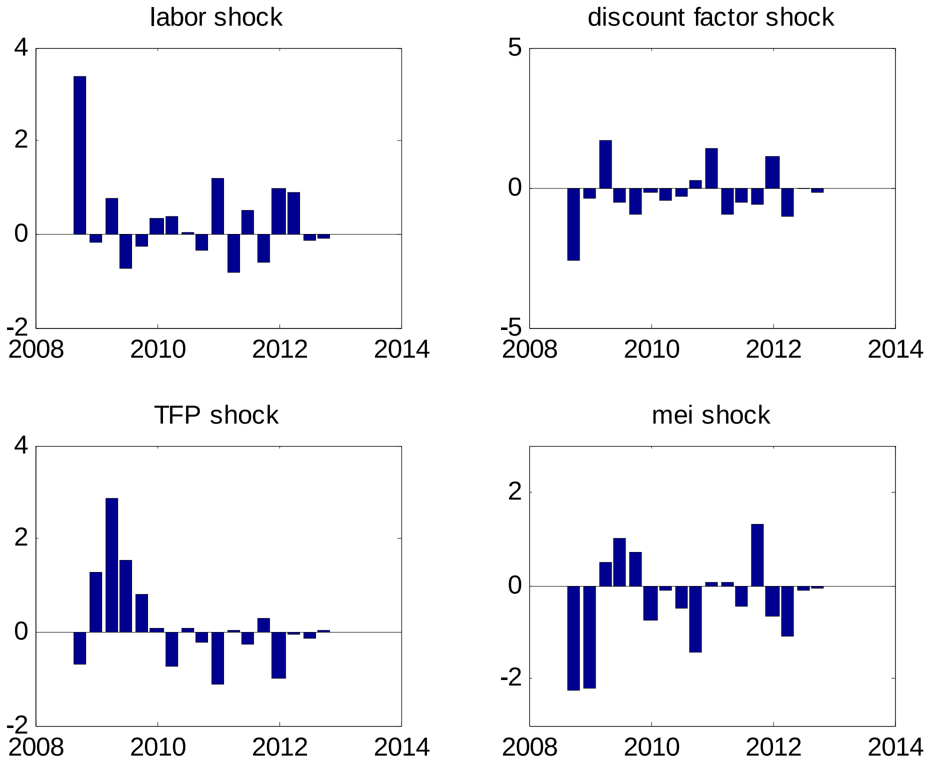
Figure 4c
Unconditional Forecast



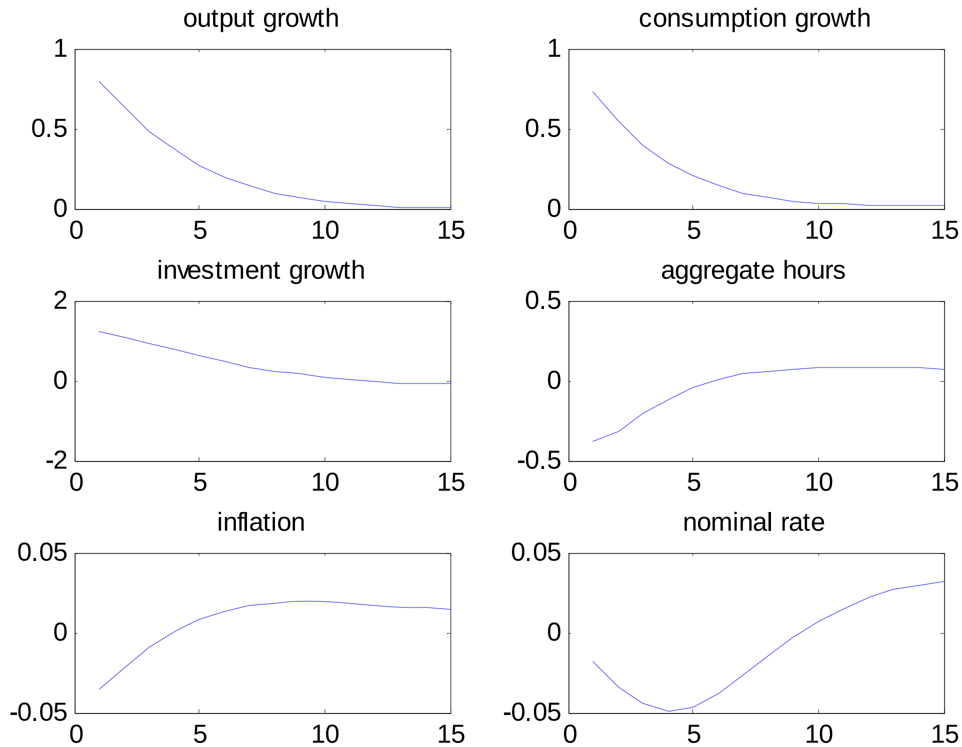
shocks:

TFP:	Total factor productivity growth shock
Gov:	Government spending shock
MEI:	Marginal efficiency of investment shock
MrkUp:	Price markup shock
Labor:	Labor supply shock
Fin:	Discount factor shock
Mpol:	Monetary policy shock

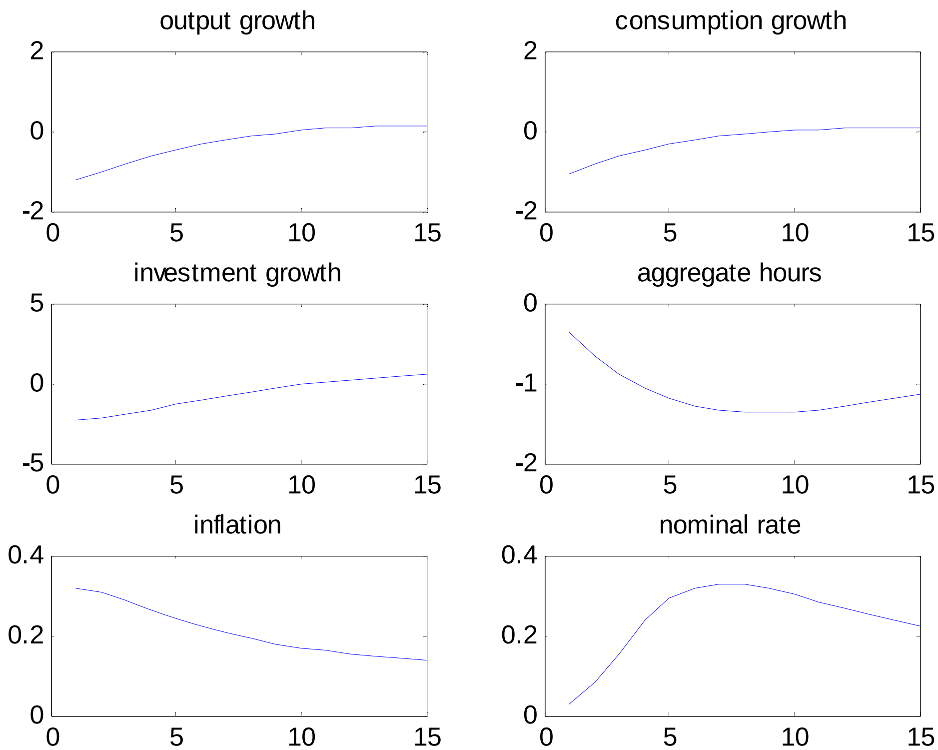
Figure 5
Smoothed Shock Estimates from Unconstrained Forecast Model
(normalized by standard deviation)



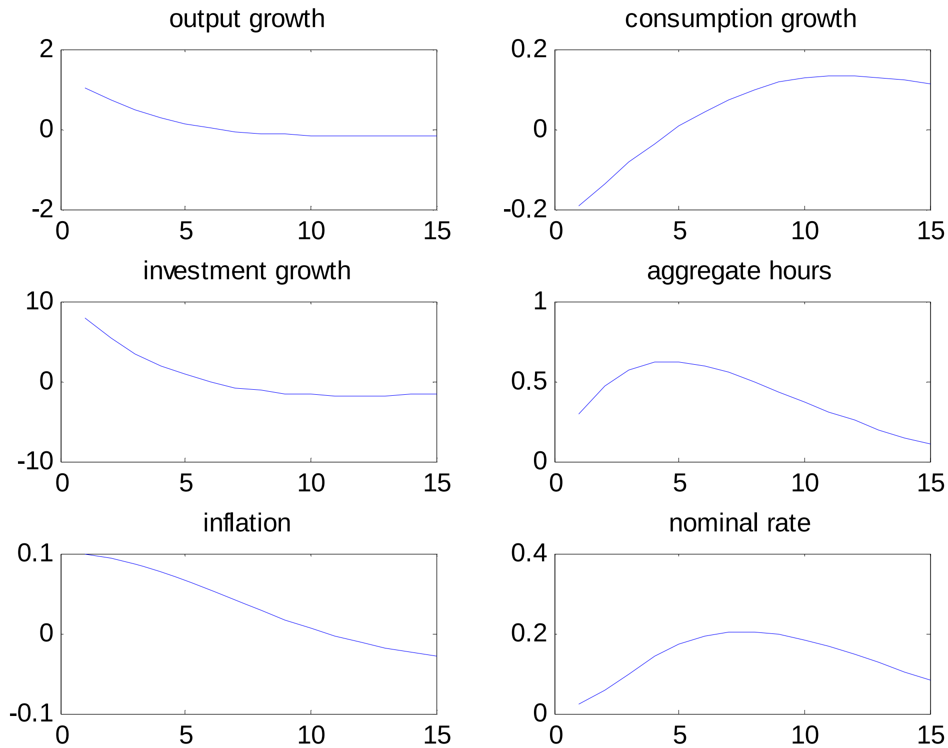
Impulse Responses to TFP shock



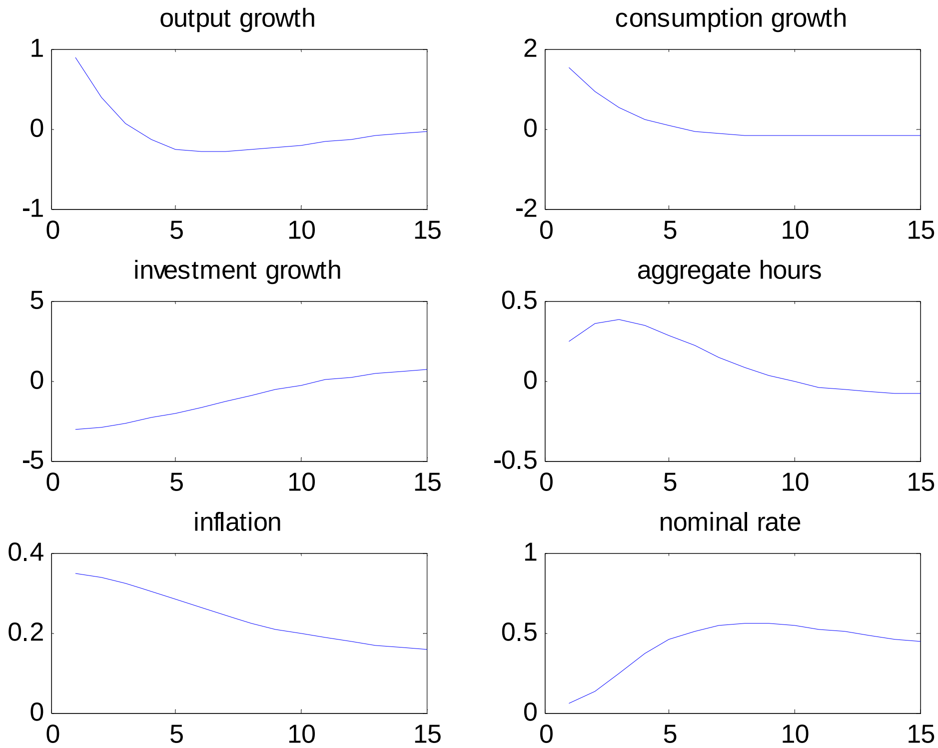
Impulse Response to Leisure Shock



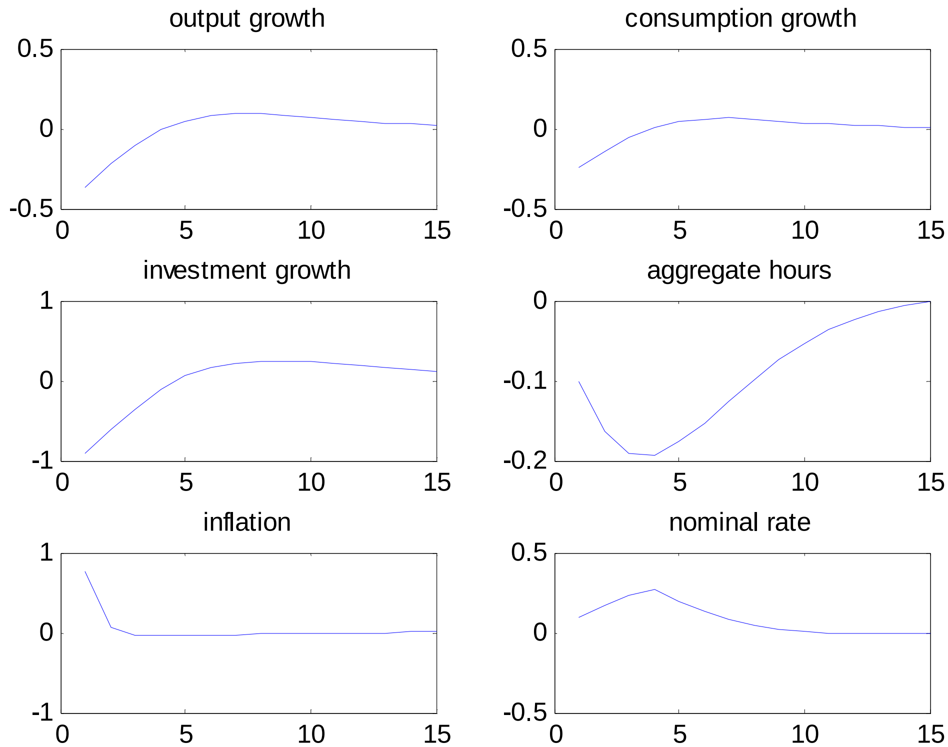
Impulse Responses to negative MEI Shock



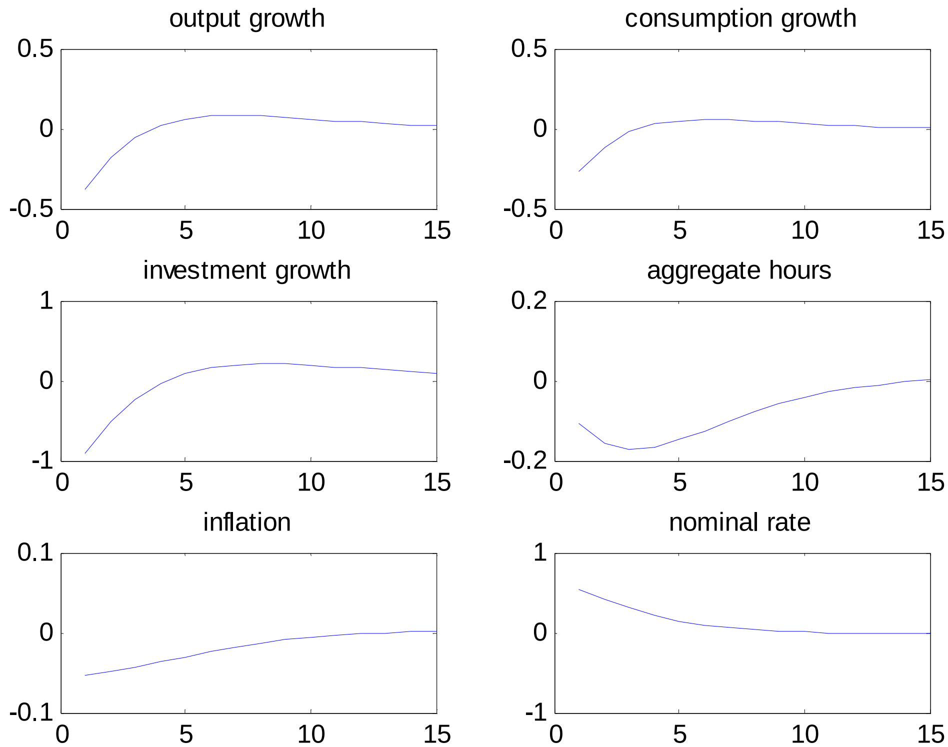
Impulse Responses to Financial Shock



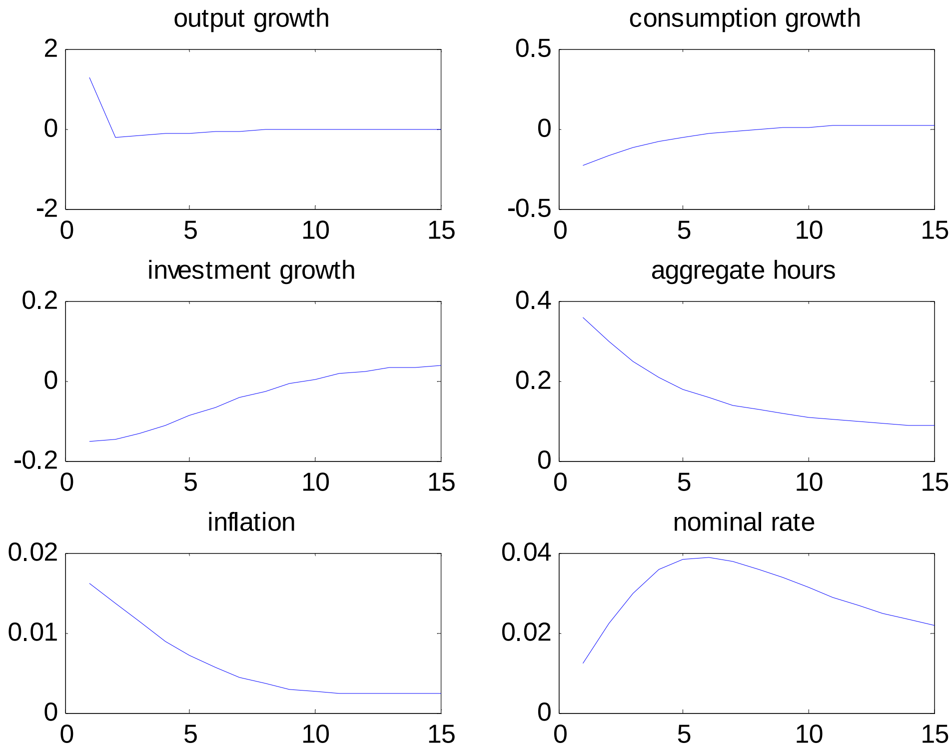
Impulse Responses to Price Markup Shock



Impulse Responses to Unanticipated Monetary Policy Shock



Impulse Responses to Govt Spending Shock



FRBNY DSGE Model: Research Directors Draft

November 12, 2012

Overview

The FRBNY DSGE model forecast is obtained using data released through 2012Q3 augmented, for 2012Q4, with observations on the federal funds rate and the Baa corporate bond spread, as well as the Board staff's forecast for real GDP growth, core PCE inflation and the NY Fed staff forecast for hours. The projections are conditional on expectations for the federal funds rate being equal to market expectations (as measured by OIS rates) through mid-2015.

The FRBNY DSGE projections for real activity are similar to those of September. Overall, the model continues to project a lackluster recovery in economic activity over the next two years. Inflation projections for 2012 and 2013 shifted downward relative to September, and remain below 2 percent through the forecast horizon. The main drivers of the subdued real GDP and inflation outlook continue to be the same forces behind the Great Recession, namely the two shocks associated with frictions in the financial system: spread and MEI (marginal efficiency of investment) shocks, whose impact is long-lasting. Accommodative monetary policy, and particularly the forward guidance, partly counteracts the financial headwinds.

General Features of the Model

The FRBNY DSGE model is a medium-scale, one-sector, dynamic stochastic general equilibrium model. It builds on the neoclassical growth model by adding nominal wage and price rigidities, variable capital utilization, costs of adjusting investment, and habit formation in consumption. The model follows the work of Christiano, Eichenbaum, and Evans (2005) and Smets and Wouters (2007), but also includes credit frictions, as in the financial accelerator model developed by Bernanke, Gertler, and Gilchrist (1999). The actual implementation of the credit frictions closely follows Christiano, Motto, and Rostagno (2009).

In this section, we briefly describe the microfoundations of the model, including the optimization problem of the economic agents and the nature of the exogenous processes. The innovations to these processes, which we refer to as "shocks," are the drivers of macroeconomic fluctuations. The model identifies these shocks by matching the model dynamics with six quarterly data series: real GDP growth, core PCE inflation, the labor share, aggregate hours worked, the effective federal funds rate (FFR), and the spread between Baa corporate bonds and 10-year Treasury yields. Model parameters are estimated from 1984Q1 to the present using Bayesian methods. Details on the structure of the model, data sources, and results of the estimation procedure can be found in the accompanying "FRBNY DSGE Model Documentation" note.

The economic units in the model are households, firms, banks, entrepreneurs, and the government. (Figure 1 describes the interactions among the various agents, the frictions and the shocks that affect the dynamics of this economy.)

Households supply labor services to firms. The utility they derive from leisure is subject to a random disturbance, which we call "labor supply" shocks (this shock is sometimes also referred to as a "leisure" shock). Labor supply shocks capture exogenous movements in labor supply due to such factors as demographics and labor market imperfections. The labor market is also subject to frictions because of nominal wage rigidities. These frictions play an important role in the extent to which various shocks affect hours worked. Households also have to choose the amount to consume and save. Their savings take the form of deposits to banks and purchases of government bills. Household preferences take into account habit persistence, a characteristic that affects their consumption smoothing decisions.

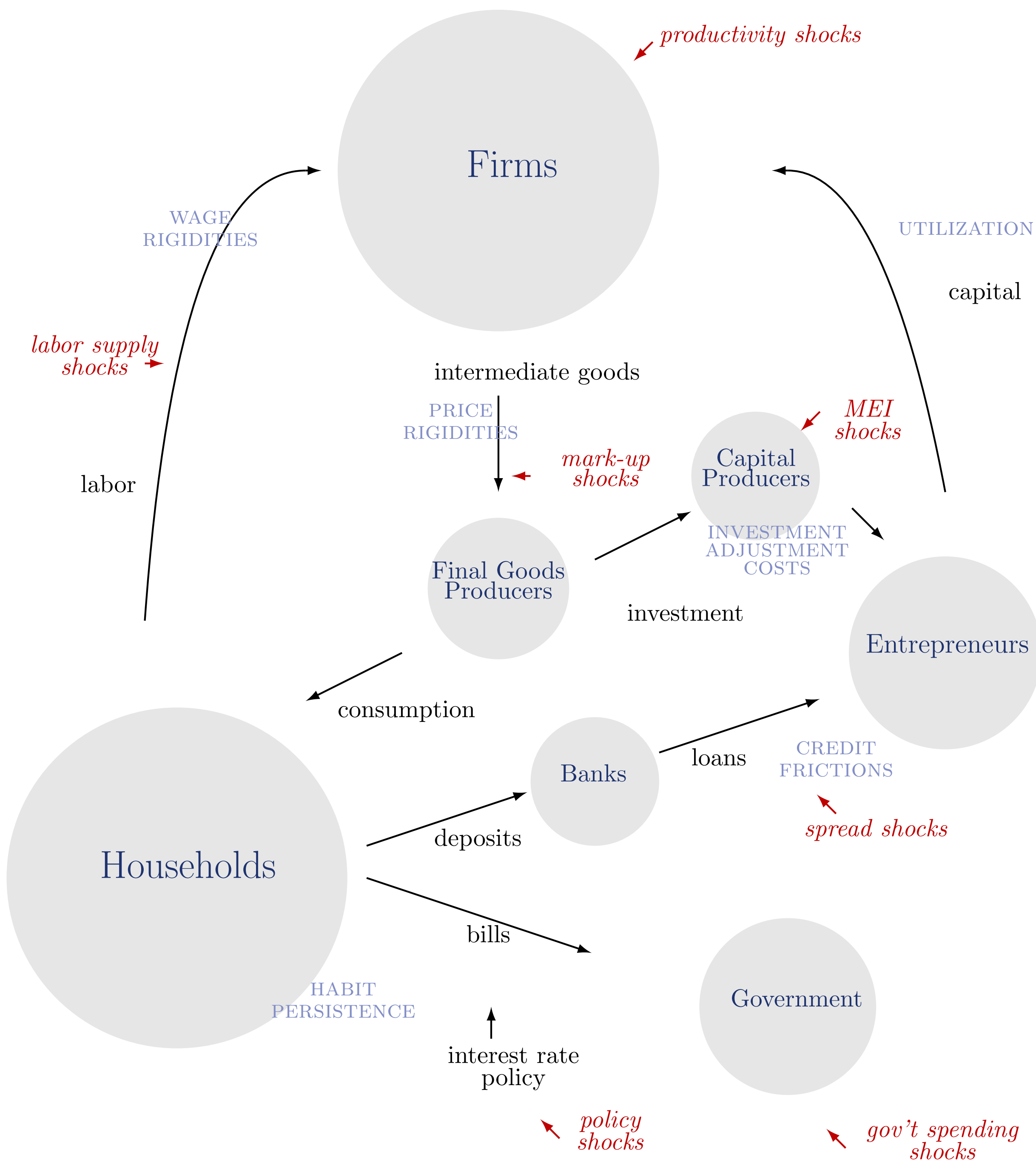
Monopolistically competitive firms produce intermediate goods, which a competitive firm aggregates into the single final good that is used for both consumption and investment. The production function of intermediate producers is subject to "total factor productivity" (TFP) shocks. Intermediate goods markets are subject to price rigidities. Together with wage rigidities, this friction is quite important in allowing demand shocks to be a source of business cycle fluctuations, as countercyclical mark-ups induce firms to produce less when demand is low. Inflation evolves in the model according to a standard, forward-looking New Keynesian Phillips curve, which determines inflation as a function of marginal costs, expected future inflation, and "mark-up" shocks. Mark-up shocks capture exogenous changes in the degree of competitiveness in the intermediate goods market. In practice, these shocks capture unmodeled inflation pressures, such as those arising from fluctuations in commodity prices.

Financial intermediation involves two actors, *banks* and *entrepreneurs*, whose interaction captures imperfections in financial markets. These actors should not be interpreted in a literal sense, but rather as a device for modeling credit frictions. Banks take deposits from households and lend them to entrepreneurs. Entrepreneurs use their own wealth and the loans from banks to acquire capital. They then choose the utilization level of capital and rent the capital to intermediate good producers. Entrepreneurs are subject to idiosyncratic disturbances in their ability to manage the capital. Consequently, entrepreneurs' revenue may not be enough to repay their loans, in which case they default. Banks protect against default risk by pooling loans to all entrepreneurs and charging a spread over the deposit rate. Such spreads vary endogenously as a function of the entrepreneurs' leverage, but also exogenously depending on the entrepreneurs' riskiness. Specifically, mean-preserving changes in the volatility of entrepreneurs' idiosyncratic shocks lead to variations in the spread (to compensate banks for changes in expected losses from individual defaults). We refer to these exogenous movements as "spread" shocks. Spread shocks capture financial intermediation disturbances that affect entrepreneurs' borrowing costs. Faced with higher borrowing costs, entrepreneurs reduce their demand for capital, and investment drops. With lower aggregate demand, there is a contraction in hours worked and real wages. Wage rigidities imply that hours worked fall even more (because nominal wages do not fall enough). Price rigidities mitigate price contraction, further depressing aggregate demand.

Capital producers transform general output into capital goods, which they sell to the entrepreneurs. Their production function is subject to investment adjustment costs: producing capital goods is more costly in periods of rapid investment growth. It is also subject to exogenous changes in the "marginal efficiency of investment" (MEI). These MEI shocks capture exogenous movements in the productivity of new investments in generating new capital. A positive MEI shock implies that fewer resources are needed to build new capital, leading to higher real activity and inflation, with an effect that persists over time. Such MEI shocks reflect both changes in the relative price of investment versus that of consumption goods (although the literature has shown the effect of these relative price changes to be small), and most importantly financial market imperfections that are not reflected in movements of the spread.

Finally, the *government* sector comprises a monetary authority that sets short-term interest rates according to a Taylor-type rule and a fiscal authority that sets public spending and collects lump-sum taxes to balance the budget. Exogenous changes in government spending are called "government" shocks (more generally, these shocks capture exogenous movements in aggregate demand). All exogenous processes are assumed to follow independent AR(1) processes with different degrees of persistence, except for i.i.d. "policy" shocks, which are exogenous disturbances to the monetary policy rule.

Figure 1: Model Structure



The Model's Transmission Mechanism

In this section, we illustrate some of the key economic mechanisms at work in the model's equilibrium. We do so with the aid of the impulse response functions to the main shocks hitting the economy, which we report in figures 7 to 13.

We start with the shock most closely associated with the Great Recession and the severe financial crisis that characterized it: the spread shock. As discussed above, this shock stems from an increase in the perceived riskiness of borrowers, which induces banks to charge higher interest rates for loans, thereby widening credit spreads. As a result of this increase in the expected cost of capital, entrepreneurs' borrowing falls, hindering their ability to channel resources to the productive sector via capital accumulation. The model identifies this shock by matching the behavior of the Baa corporate bond rate over 10-year Treasuries, and the spread's comovement with output growth, inflation, and the other observables. Figure 7 shows the impulse responses of the variables used in the estimation to a one-standard-deviation innovation in the spread shock. An innovation of this size increases the observed spread by roughly 35 basis points (bottom right panel). This leads to a reduction in investment and consequently to a reduction in output growth (top left panel) and hours worked (top right panel). The fall in the level of hours is fairly sharp in the first year and persists for many quarters afterwards, leaving the labor input not much higher than at the trough five years after the impulse. Of course, the effects of this same shock on GDP growth, which roughly mirrors the change in the level of hours, are much more short-lived. Output growth returns to its steady state level about two years after the shock hits, but it barely moves above it after that, implying no catch up of the level of GDP towards its previous trend. The persistent drop in the level of economic activity due to the spread shock also leads to a prolonged decline in real marginal costs - which in this model map one-to-one into the labor share (middle left panel)- and, via the New Keynesian Phillips curve, in inflation (middle right panel). Finally, policymakers endogenously respond to the change in the inflation and real activity outlook by cutting the federal funds rate (bottom left panel).

Very similar considerations hold for the MEI shock, which represents a direct hit to the "technological" ability of entrepreneurs to transform investment goods into productive capital, rather than an increase in their funding cost. Although the origins of these two shocks are different, the fact that they both affect the creation of new capital implies very similar effects on the observable variables, as shown by the impulse responses in figure 8. In particular, a positive MEI shock also implies a very persistent increase in investment, output and hours worked, as well as in the labor share and hence inflation. The key difference between the two impulses, which is also what allows us to tell them apart empirically, is that the MEI shock leaves spreads virtually unchanged (bottom right panel).

Another shock that plays an important role in the model, and whose estimated contribution to the Great Recession and its aftermath increased in light of the latest data revisions, is the TFP shock. As shown in figure 9, a positive TFP shock has a large and persistent effect on output growth, even if the response of hours is muted in the first few quarters (and slightly negative on impact). This muted response of hours is due to the presence of nominal rigidities, which prevent an expansion of aggregate demand sufficient to absorb the increased ability of the economy to supply output. With higher productivity, marginal costs and thus the labor share fall, leading to lower inflation. The policy rule specification implies that this negative correlation between inflation and real activity, which is typical of supply shocks, produces countervailing forces on the interest rate, which as a result moves little. These dynamics make the TFP shock particularly suitable to account for the first phase of the recovery, in which GDP growth was above trend, but hours and inflation remained weak. With the recent softening of the expansion, though, the role of TFP shocks is fading.

The last shock that plays a relevant role in the current economic environment is the mark-up shock, whose impulse response is depicted in figure 10. This shock is an exogenous source of inflationary pressures, stemming from changes in the market power of intermediate goods producers. As such, it leads to higher inflation and lower real activity, as producers reduce supply to increase their desired markup. Compared to those of the other prominent supply shock in the model, the TFP shock, the effects of markup-shocks feature significantly less persistence. GDP growth falls on impact after mark-ups increase, but returns above average after about one year. Inflation is sharply higher, but only for a couple of quarters, leading to a temporary spike in the nominal interest rate, as monetary policy tries to limit the pass-through of the shock to inflation. Unlike in the case of TFP shocks, however, hours fall immediately, mirroring the behavior of output.

Forecasts

	2012 (Q4/Q4)		2013 (Q4/Q4)		2014 (Q4/Q4)		2015 (Q4/Q4)	
Unconditional Forecast	Nov	Sep	Nov	Sep	Nov	Sep	Nov	Sep
Core PCE	1.5	1.6	1.0	1.2	1.4	1.5	1.5	1.6
Inflation	(1.5,1.6)	(1.4,1.7)	(0.4,1.6)	(0.4,1.8)	(0.4,2.0)	(0.5,2.2)	(0.6,2.3)	(0.7,2.4)
Real GDP	1.8	1.9	2.4	2.3	1.8	1.8	1.2	1.3
Growth	(1.8,1.9)	(1.2,2.4)	(-0.6,4.3)	(-1.1,4.6)	(-1.9,4.4)	(-1.8,4.5)	(-2.3,4.2)	(-2.1,4.3)

	2012 (Q4/Q4)		2013 (Q4/Q4)		2014 (Q4/Q4)		2015 (Q4/Q4)	
Conditional Forecast*	Nov	Sep	Nov	Sep	Nov	Sep	Nov	Sep
Core PCE	1.7	1.7	0.9	1.3	1.2	1.5	1.5	1.6
Inflation	(1.7,1.7)	(1.6,1.9)	(0.2,1.4)	(0.5,1.8)	(0.3,1.8)	(0.5,2.1)	(0.5,2.2)	(0.6,2.3)
Real GDP	1.8	2.0	2.7	2.4	2.3	1.8	1.6	1.3
Growth	(1.8,1.8)	(1.3,2.5)	(-0.3,4.6)	(-0.9,4.6)	(-1.4,4.9)	(-1.8,4.6)	(-1.9,4.5)	(-2.0,4.4)

*The unconditional forecasts use data up to 2012Q2, the quarter for which we have the most recent GDP release, as well as the federal funds rate and spreads data for 2012Q4. In the conditional forecasts, we further include the 2012Q4 Board staff's projections for GDP growth, core PCE inflation, and the 2012Q4 FRBNY staff projections for hours worked as additional data points. Numbers in parentheses indicate 68 percent probability intervals.

We detail the forecast of three main variables over the horizon 2012-2015: real GDP growth, core PCE inflation and the federal funds rate. The federal funds rate expectations in the model are set equal to market expectations for the federal funds rate (as measured by OIS rates) through mid-2015. We capture policy anticipation by adding anticipated monetary policy shocks to the central bank's reaction function, following Laseen and Svensson (2009).

The table above presents Q4/Q4 forecasts for real GDP growth and inflation for 2012-2015, with 68 percent probability intervals. We include two sets of forecasts. The *unconditional* forecasts use data up to 2012Q3, the quarter for which we have the most recent GDP release, as well as the federal funds rate and spreads data for 2012Q4 (we use the average realizations for the quarter up to the forecast date). In the *conditional* forecasts, we further include the 2012Q4 Board staff's projections for GDP growth and core PCE inflation, and 2012Q4 FRBNY staff projections for hours worked as additional data points (as of November 7, projections for 2012Q4 are 1.8 percent for output growth, 1.5 percent for core PCE inflation, and 0 percent growth for hours worked). Treating the 2012Q4 forecasts as data allows us to incorporate into the DSGE forecasts information about the current quarter. In addition to providing the current forecasts, for comparison we report the forecasts included in the DSGE memo circulated for the September FOMC meeting. Figure 2 presents quarterly forecasts, both unconditional (left panels) and conditional (right panels). In the graphs, the black line represents data, the red line indicates the mean forecast, and the shaded areas mark the uncertainty associated with our forecast as 50, 60, 70, 80 and 90 percent probability intervals. Output growth and inflation are expressed in terms of percent annualized rates, quarter to quarter. The interest rate is the annualized quarterly average. The bands reflect both parameter uncertainty and shock uncertainty. Figure 3 compares the current forecasts with those produced for the September FOMC meeting. Our discussion will mainly focus on the conditional forecasts, which are those included in the memo for the FOMC.

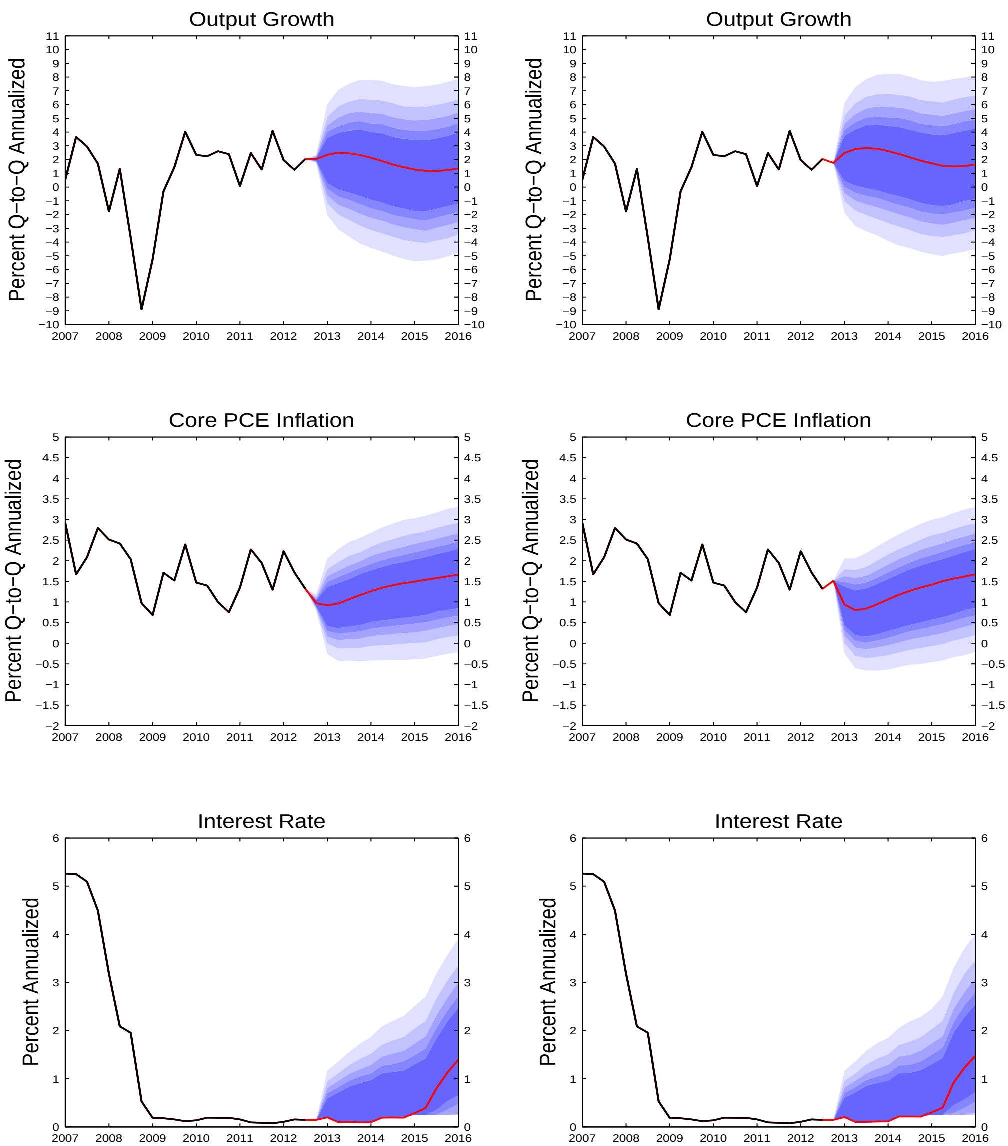
The model still projects a lackluster recovery in economic activity, with output growth in the neighborhood of 2 percent throughout the forecast horizon. Output growth in 2012Q3 and its 2012Q4 projection are roughly in line with the September's DSGE model projections. Hence our current output forecasts are broadly similar to those in September. Conditional output growth forecasts for 2013, 2014, and 2015 (Q4/Q4) moved to 2.7, 2.3, and 1.6 percent from 2.3, 1.7, and 1.3 percent, respectively, in September. There is moderate uncertainty around the real GDP forecasts, with 68 percent bands for the conditional forecasts covering the interval -0.6 to 4.3 percent in 2013 (Q4/Q4). Unconditional output forecasts for 2012 (Q4/Q4) are broadly similar to the conditional forecasts and little changed from September.

The forecast distribution for inflation moved down relative to September. Core PCE inflation in 2012Q3 and the Board staff's projected value for 2012Q4 are slightly different from the DSGE model projection, weaker by about 25 basis points in Q3, and just a bit stronger in Q4. The model attributes the over-prediction in Q3 to having over-estimated the impact of forward guidance on inflation, and the under-prediction in Q4 to a mark-up shock, which captures high frequency movements in inflation such as those due to energy prices. Since forward guidance has more persistent effects than mark-up shocks, the projections are weaker than in September. The 68 percent probability bands for inflation in 2013, 2014, and 2015 (Q4/Q4) are within the 1-2 percent interval for the conditional forecasts, implying that the model places high probability on inflation realizations below the long-run FOMC target. Unconditional inflation forecasts are slightly lower than the conditional ones.

Finally, as mentioned above, we constrain the federal funds rate expectations to be equal to the expected federal fund rate as measured by the OIS rates until 2015Q2; after that the federal funds rate raises gradually but remains below 2 percent until the end of 2015.

Figure 2: Forecasts

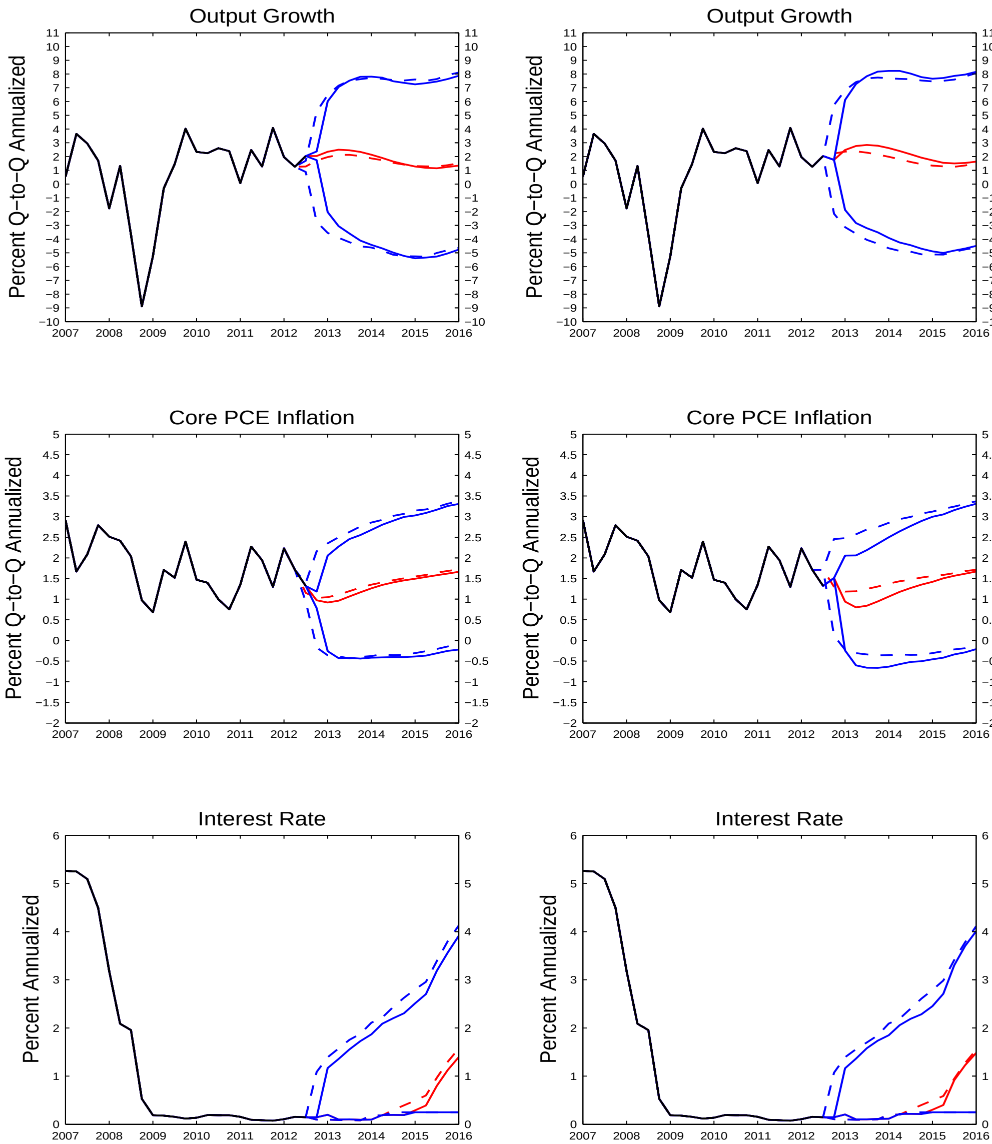
Unconditional **Conditional**



Black lines indicate data, red lines indicate mean forecasts, and shaded areas mark the uncertainty associated with our forecast as 50, 60, 70, 80, and 90 percent probability intervals.

Figure 3: Change in Forecasts

Unconditional Conditional



Solid and dashed red lines represent the mean for current and September's forecast, respectively. Solid and dashed blue lines represent 90 percent probability intervals.

Interpreting the Forecasts

We use the shock decomposition shown in Figure 4 to interpret the forecasts. This figure quantifies the importance of each shock for output growth, core PCE inflation, and the federal funds rate (FFR) from 2007 on, by showing the extent to which each of the disturbances contributes to keeping the variables from reaching their long-run values. Specifically, in each of the three panels the solid line (black for realized data, red for mean forecast) shows the variable in deviation from its steady state (for output, the numbers are per capita, as the model takes population growth as exogenous; for both output and inflation, the numbers are quarter-to-quarter annualized). The bars represent the contribution of each shock to the deviation of the variable from steady state, that is, the counterfactual values of output growth, inflation, and the federal funds rate (in deviations from the mean) obtained by setting all other shocks to zero. By construction, for each observation the bars sum to the value of the solid line.

The figure shows that all three variables of interest are currently below their steady-state values, and are forecasted to stay so through the end of the forecast horizon. The outlook is driven by two main factors. On the one hand, the headwinds from the financial crisis, as captured by the effect of both spread and MEI (marginal efficiency of investment) shocks, result in a subdued recovery, low real marginal costs, and consequently low inflation. The impact of these shocks on the recovery is long-lasting. On the other hand, accommodative monetary policy, and particularly the forward looking language, plays an important role in counteracting the financial headwinds, and lifts up output and inflation.

The role played by spread and MEI shocks is quite evident in the shock decomposition for inflation and interest rates, which shows that MEI, and to a lesser extent, spread shocks (azure and purple bars, respectively) play a key role in keeping these two variables below steady state. This feature of the DSGE forecast is less evident for real output growth, as the contribution of MEI shocks seems small, particularly toward the end of the forecast horizon, and the contribution of spread shocks is negligible (and positive). However, recall that a small, but still negative, effect on output *growth* implies that the effect of the MEI shocks on the *level* of output is getting *larger*, even several quarters after the occurrence of the shock. Similarly, the fact that the growth impact of spread shock is positive but very small implies that the level of output is very slowly returning to trend. This is evident in the protracted effect of spread and MEI shocks on aggregate hours, shown in the impulse responses of Figures 7 and 8, respectively, and discussed above. In turn, the fact that economic activity is well below trend pushes inflation and consequently interest rates (given the Fed's reaction function) below steady state.

More insight on the interpretation of the "financial" shocks – MEI and spread shocks – can be obtained from Figure 5. This figure shows the recent history of the shocks, expressed in standard deviation units. The panel labeled "Spread" shows that during the Great Recession there were two large spread shocks, one in 2007 and one in concurrence with the Lehman Brothers default. Such positive spread shocks raise spreads and have negative impact on economic activity (see Figure 7). The panel labeled "MEI" in Figure 5 shows that MEI shocks were mostly negative from 2009 onwards, that is, *after* the end of the recession. Such negative MEI shocks have a negative impact on economic activity (see Figure 8).

Monetary policy shocks were largely expansionary in recent history, and especially in 2008. These shocks include both contemporaneous and anticipated deviations from the feedback rule. The impact of policy shocks on the interest rate is currently very small, implying that the level of the interest rate is not too far from that implied by the estimated policy rule. Later in the forecast horizon the impact of these shocks becomes larger, and reaches one percentage point in 2015: the impact of the forward guidance, combined with the interest rate smoothing component of the policy which limits quarter-to-quarter adjustments, implies that the renormalization path is lower than that implied by the estimated rule.

Policy shocks play an important role in pushing inflation and output upward both in the immediate aftermath of the recession and in the current period. However, the impact of policy on the *level* of output starts to wane by the end of 2012. This implies that the effect of policy on *growth* is actually negative after that, which explains why growth is still at or below trend by the end of 2014. This is partly because the stimulative effect of the forward guidance is front-loaded, and hence has the largest impact when it is first implemented.

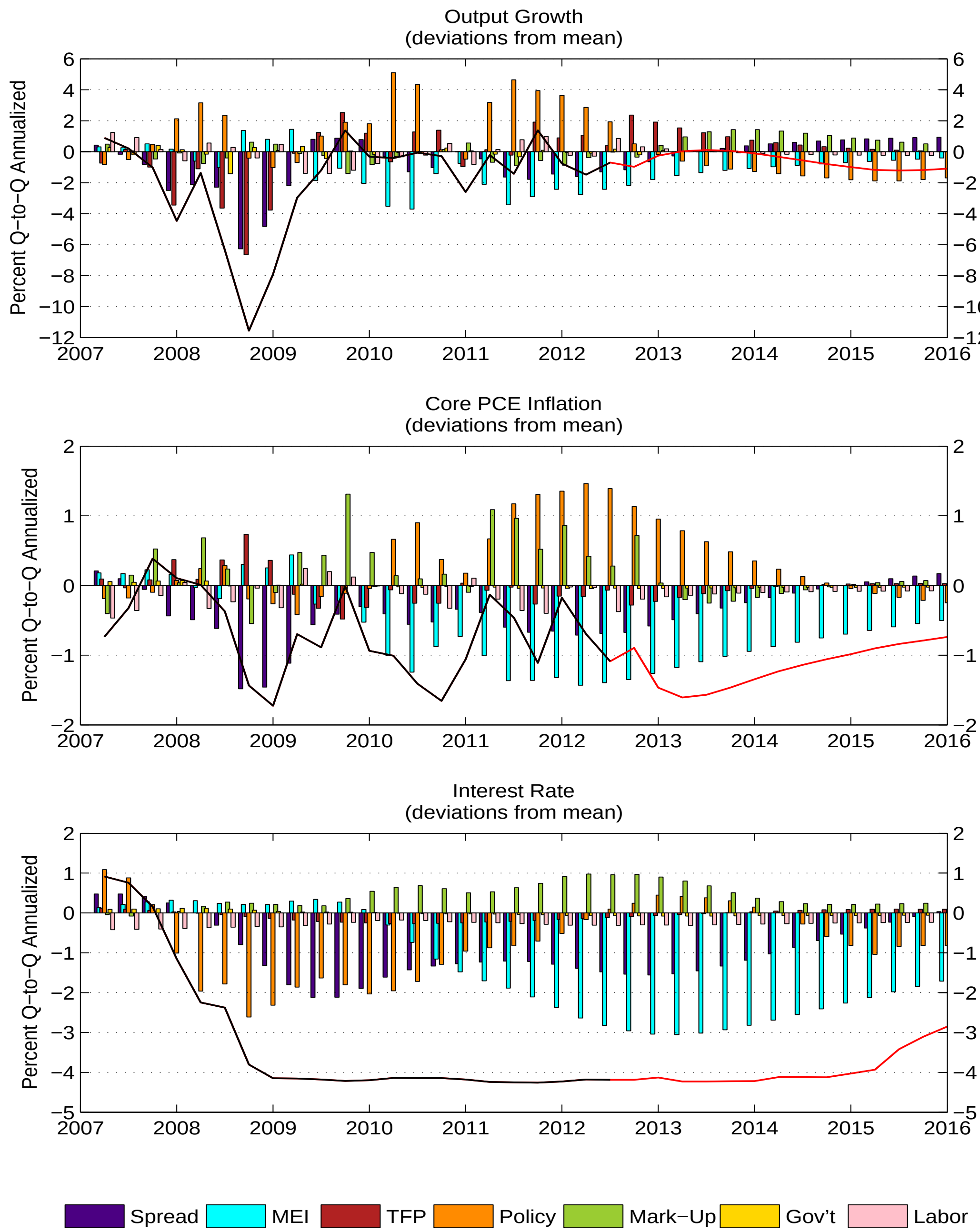
The model attributes much of the rise in core inflation in the first half of 2011 and in 2012Q1 to price mark-up shocks. Increases in mark-ups in our monopolistically competitive setting push inflation above marginal costs and reduce output. Figure 10 shows that mark-up shocks capture large but transitory movements in inflation, such as those due to oil price fluctuations. As a result, the large positive mark-up shock behind the up-tick in inflation in recent quarters has almost no effect on the inflation forecasts. Since output is returning quickly to trend following mark-up shocks, these actually contribute positively to output growth from 2013 onward.

Forecasts without Incorporating Federal Funds Rate Expectations

As mentioned above, in order to incorporate market expectations into our outlook we add federal funds rate expectations through 2015Q2 to the usual set of observables, as described in more detail in the FRBNY DSGE Model Documentation (we actually add federal funds rate expectations to the observables since the near-zero interest rate policy came into place in late 2008). We correspondingly change the model by adding anticipated monetary policy shocks to the central bank's reaction function, following Laseen and Svensson (2009). The model can therefore match the new information (the FFR expectations) in two different ways: (i) via the anticipated policy shocks, which capture pre-announced deviations from the estimated policy rule (as in "we expect interest rates to be low because monetary policy is unusually accommodative") ; and (ii) by changing its assessment of the state of the economy (as in "we expect interest rates to be low because the state of the economy is worse than previously estimated"). The two channels capture the exogenous and endogenous component of monetary policy, respectively. We discussed the first channel – the effect of anticipated shocks – in the previous section.

Figure 6 shows our baseline unconditional (left panels) and conditional (right panels) forecasts (solid lines) as well as the forecasts without incorporating federal funds rate expectations (dashed lines). The figure shows that the model interprets the data on expected future federal funds rates as signaling a relatively weak state of the economy and a sluggish expansion in the next few years. When abstracting from the information provided by expected future federal funds rates, forecasts are indeed a bit more optimistic. Output growth and inflation forecasts for 2015 are higher by roughly 100 and 50 basis points, respectively, despite a more rapid tightening of monetary policy. The latter policy tightening occurs sooner when expected future federal funds rates are not constrained, with the federal funds rate going to 1 percent in the current quarter and about 3 percent by the end of the forecast horizon.

Figure 4: Shock Decomposition



]

The shock decomposition is presented for the conditional forecast. The solid lines (black for realized data, red for mean forecast) show each variable in deviation from its steady state. The bars represent the shock contributions; specifically, the bars for each shock represent the counterfactual values for the observables (in deviations from the mean) obtained by setting all other shocks to zero.

Figure 5: Shock Histories

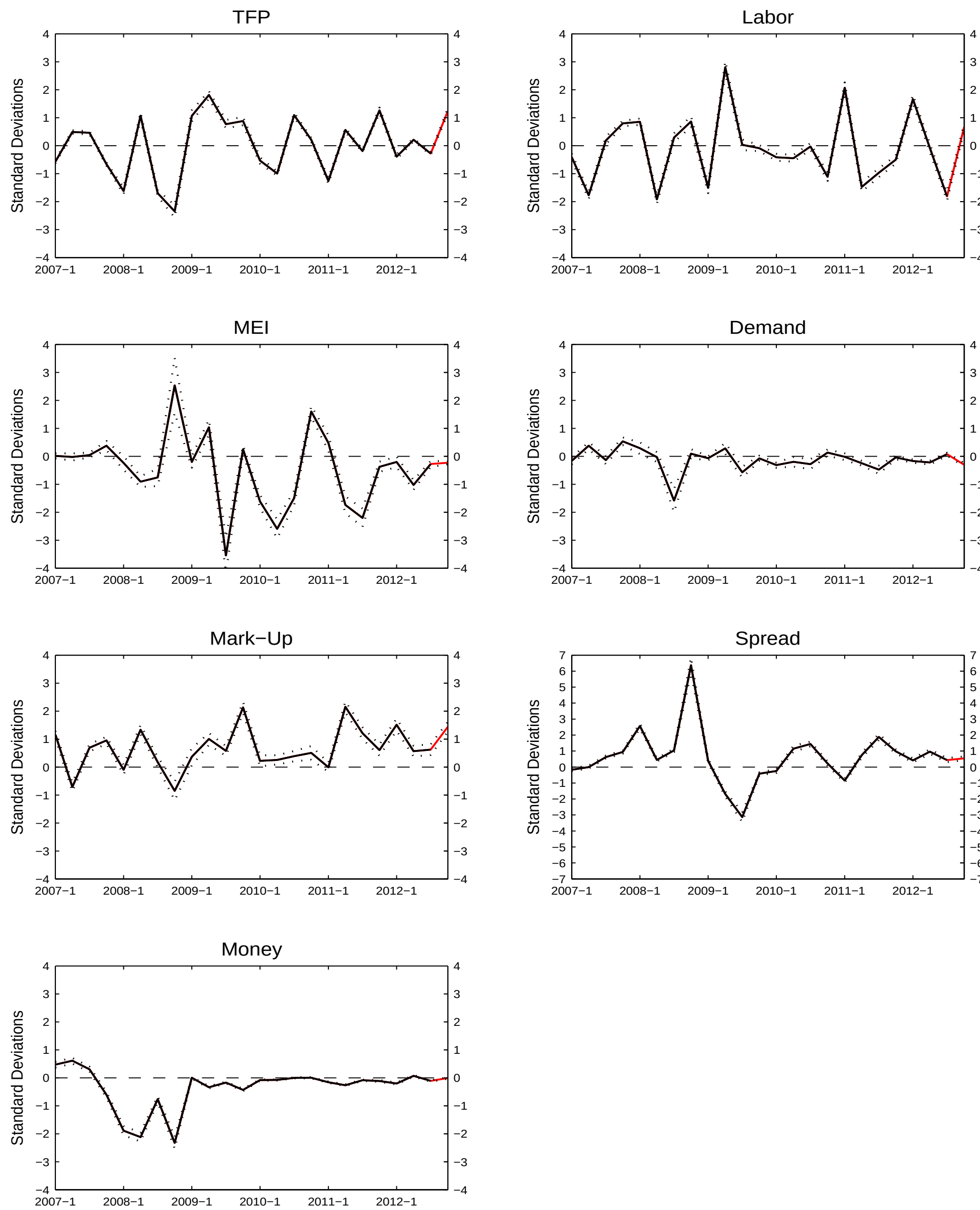
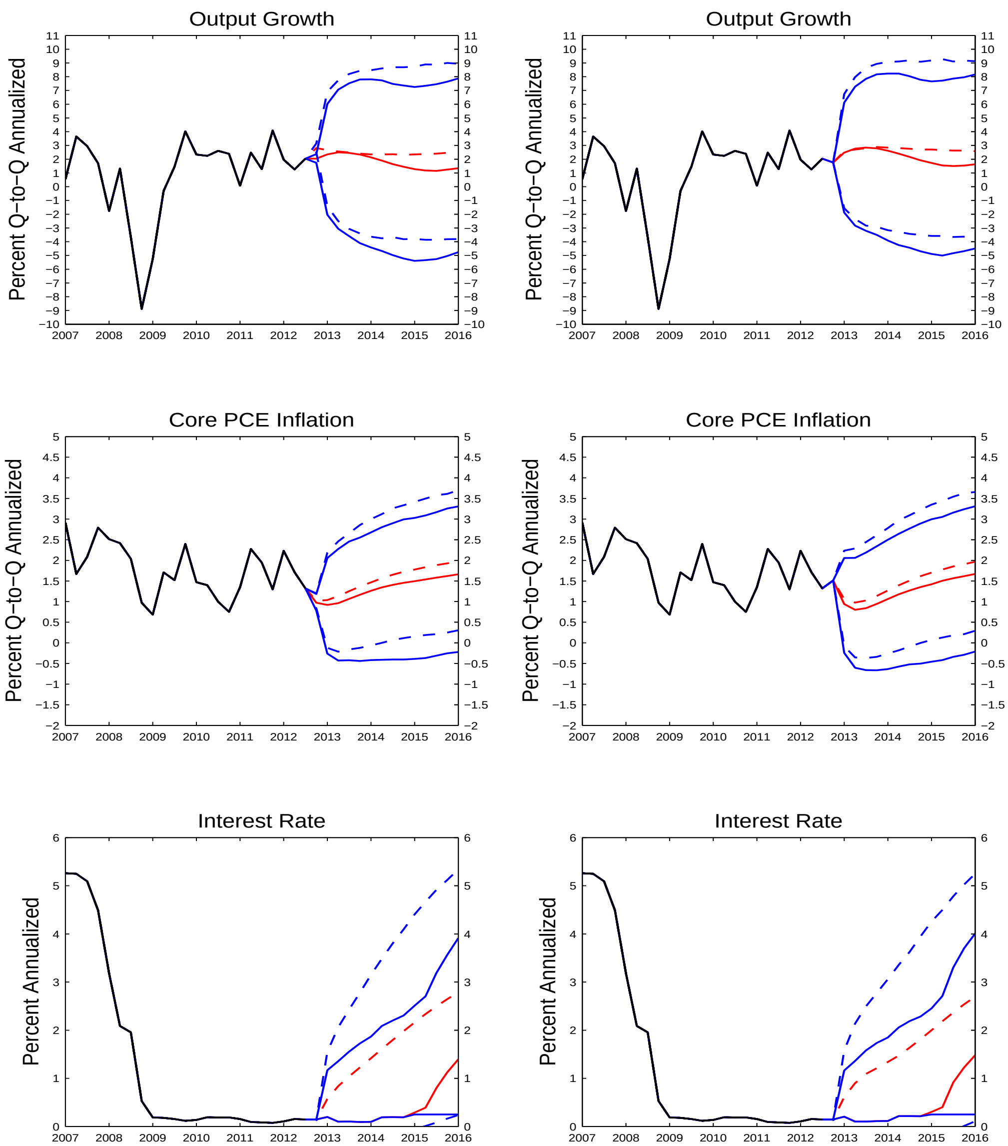


Figure 6: Effect of Incorporating FFR Expectations

Unconditional **Conditional**



Solid and dashed red lines represent the mean for the forecast with and without incorporating FFR expectations, respectively. Solid and dashed blue lines represent 90 percent probability intervals.

Figure 7: Responses to a Spread Shock

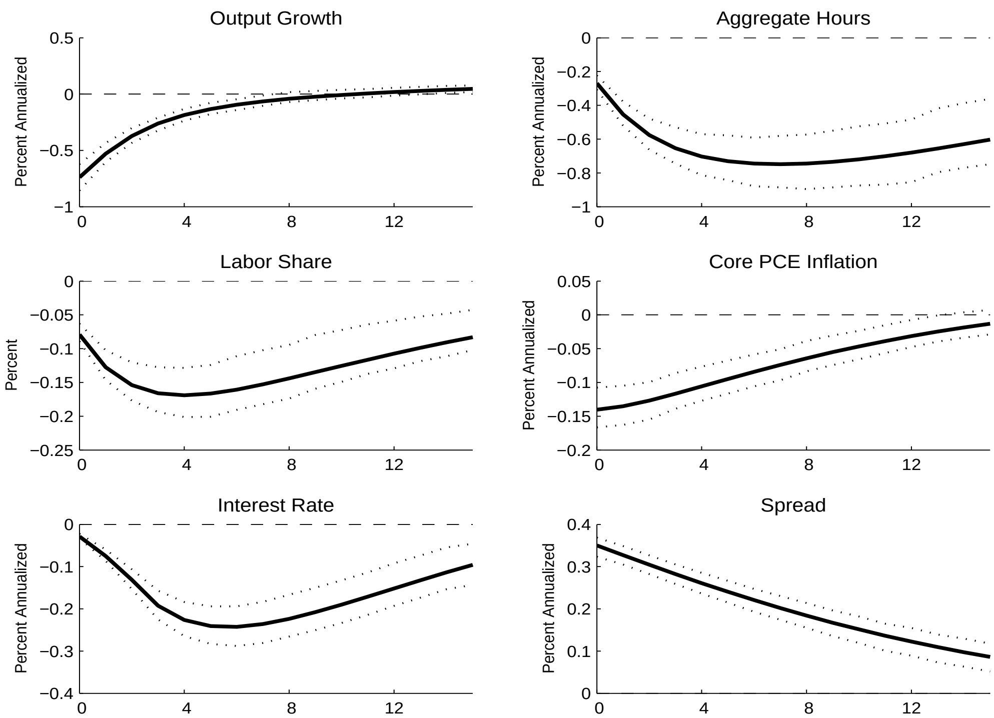


Figure 8: Responses to an MEI Shock

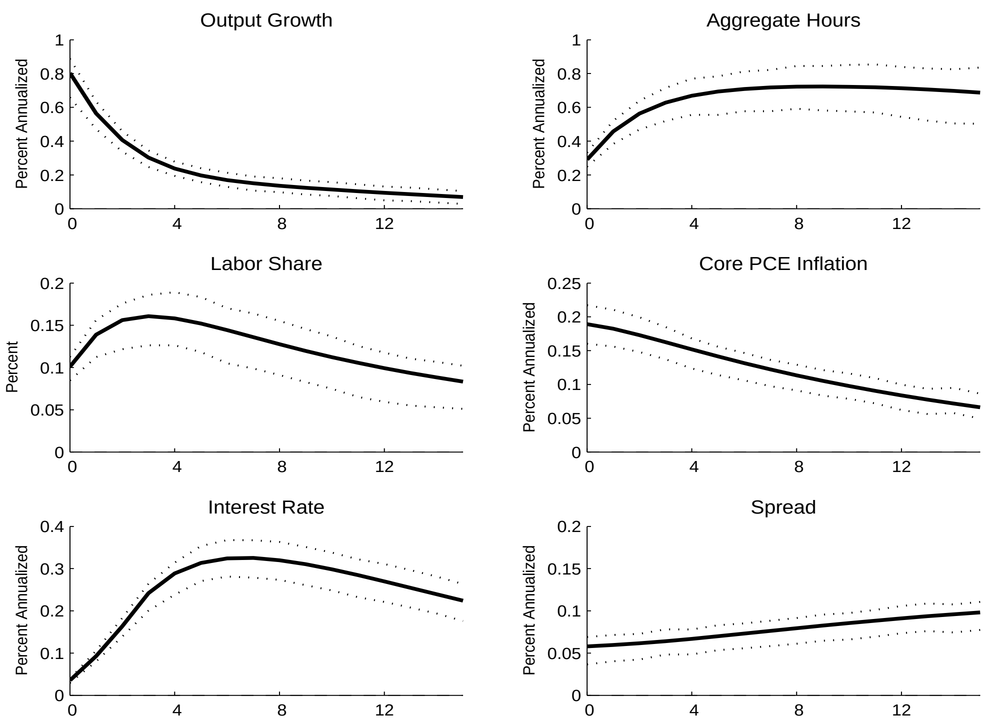


Figure 9: Responses to a TFP Shock

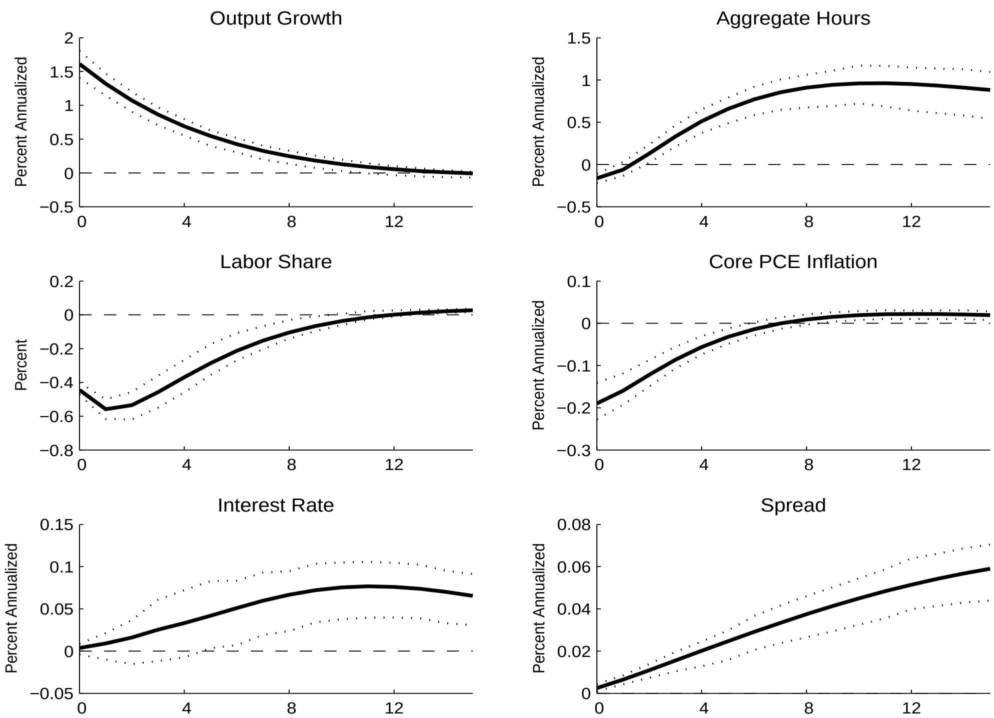


Figure 10: Responses to a Mark-up Shock

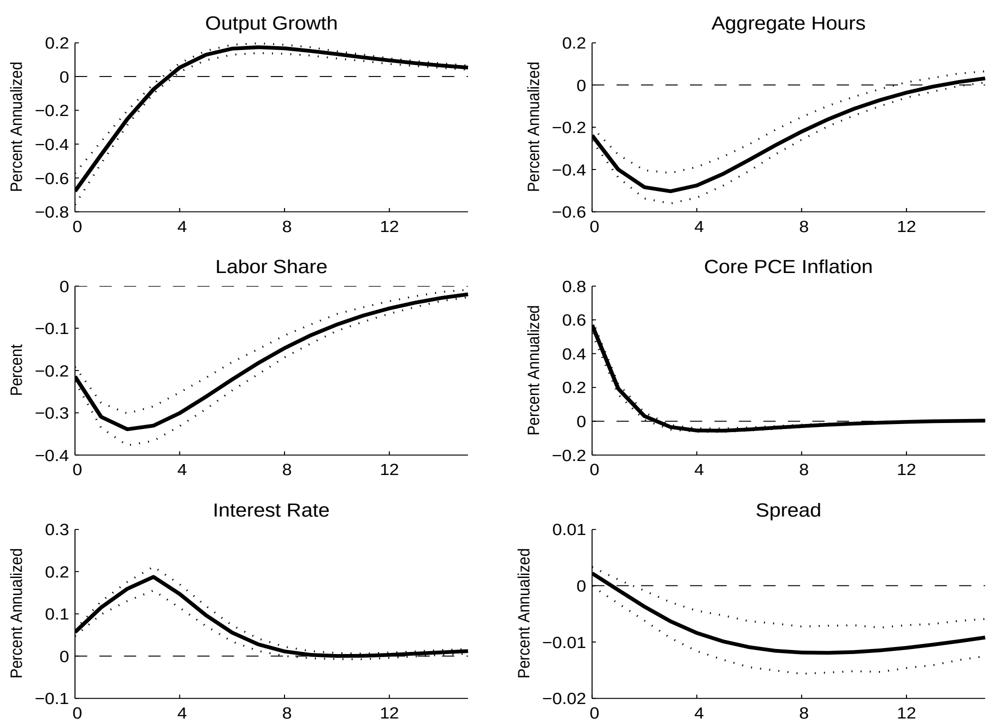


Figure 11: Responses to a Monetary Policy Shock

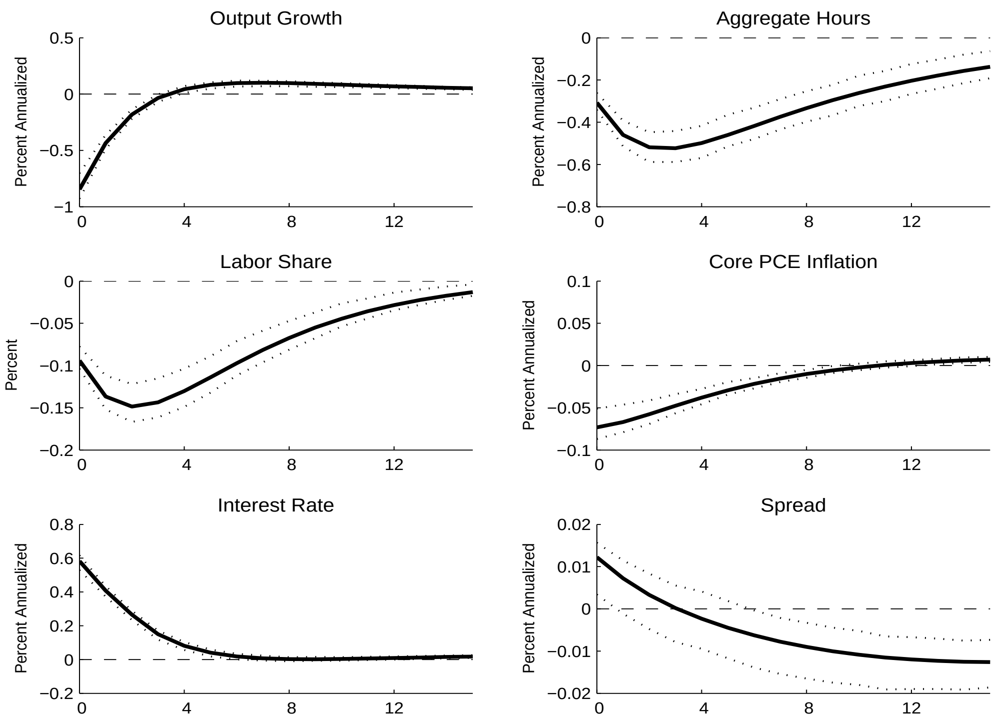


Figure 12: Responses to a Labor Supply Shock

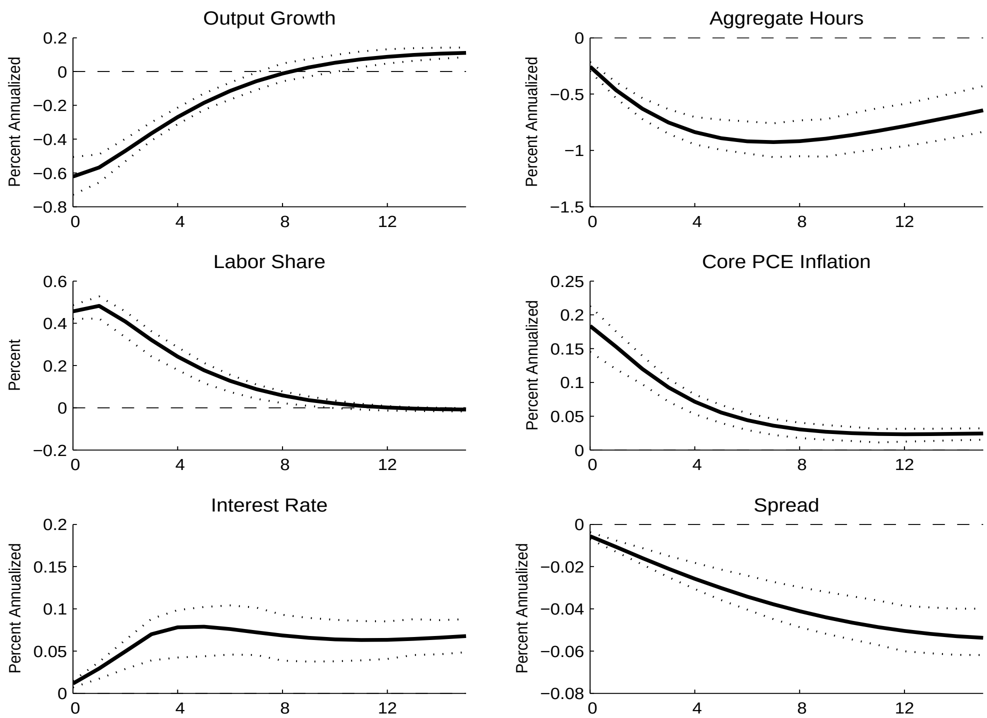
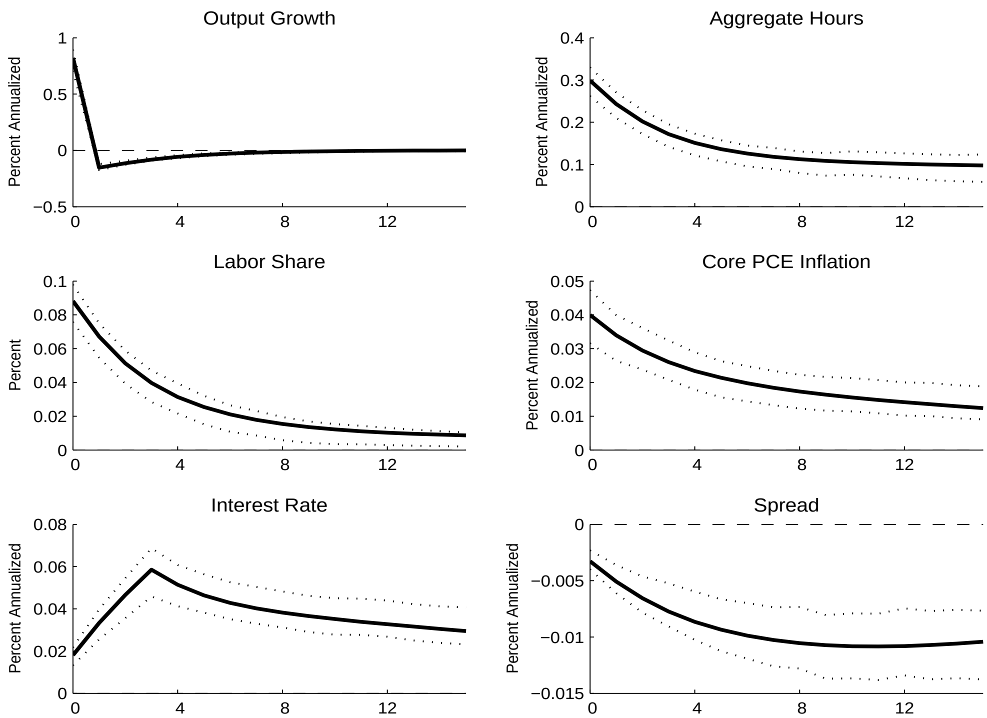


Figure 13: Responses to a Government Spending Shock



References

[1] **Bernanke, Ben, Mark Gertler and Simon Gilchrist**, "The Financial Accelerator in a Quantitative Business Cycle Framework," in J.B. Taylor and M. Woodford, eds., Handbook of Macroeconomics, vol. 1C, Amsterdam: North-Holland, 1999.

[2] **Calvo, Guillermo**, "Staggered Prices in a Utility-Maximizing Framework," *Journal of Monetary Economics*, 1983, *12*, 383–398.

[3] **Christiano, Lawrence, Martin Eichenbaum, and Charles Evans**, "Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy," *Journal of Political Economy*, 2005, *113*, 1–45.

[4] **Christiano, Lawrence, Roberto Motto, and Massimo Rostagno**, "Financial Factors in Economic Fluctuations," Unpublished, 2009.

[5] **Laseen, Stefan and Lars E. O. Svensson**, "Anticipated Alternative Instrument-Rate Paths in Policy Simulations," NBER Working Paper No. w14902, 2009.

[6] **Smets, Frank and Raphael Wouters**, "Shocks and Frictions in US Business Cycles: A Bayesian DSGE Approach," *American Economic Review*, 2007, *97* (3), 586 – 606.

Federal Reserve Bank of Chicago

Subject: Summary of Chicago Fed DSGE Model for Academic Researchers

From: Scott Brave Jeffrey R. Campbell Jonas D.M. Fisher Alejandro Justiniano

Date: November 27, 2012

Overview

In this memo, we describe the Chicago Fed's estimated dynamic stochastic general equilibrium model. This framework yields a history of identified structural shocks, which we apply to illuminate recent macroeconomic developments. To aid in the understanding of these results, we follow them with summaries of the model's structure, the data and methodology employed for estimation, and the estimated model's dynamic properties.

In several respects, the Chicago Fed DSGE model resembles many other New Keynesian frameworks. There is a single representative household that owns all firms and provides the economy's labor. Production uses capital, differentiated labor inputs, and differentiated intermediate goods. The prices of all differentiated inputs are "sticky", so standard forward-looking Phillips curves connect wage and price inflation with the marginal rate of substitution between consumption and leisure and marginal cost, respectively. Other frictions include investment adjustment costs and habit-based preferences.

There are, however, several features of the model which distinguish it from these frameworks. For instance, in addition to the usual current monetary policy shock in the Taylor rule, we account for short-term guidance regarding the future path of the federal funds rate. A factor structure estimated from federal funds and Eurodollar futures prices is used to identify both a *current policy factor* and a *forward guidance factor*.

Also included in our Taylor rule is a shock which dominates changes in long-run expected inflation. We refer to this shock, captured in a shifting intercept in the

Taylor rule, as the *inflation anchor shock*, and we discipline its fluctuations with data on long-term inflation expectations from the Survey of Professional Forecasters.

Another distinguishing feature of the Chicago model is the use of multiple price indices. Alternative available indices of inflation are decomposed into a single model-based measure of consumption inflation and idiosyncratic (series specific) disturbances that allow for persistent deviations from this common component. Estimation uses a factor model with the common factor derived from the DSGE framework.

The model also incorporates a financial accelerator mechanism. We introduce risk-neutral entrepreneurs into the New Keynesian framework who purchase capital goods from capital installers using a mix of internal and external resources. These entrepreneurs optimally choose their rate of capital utilization and rent the effective capital stock to goods producing firms. The dependence on internal resources explicity links fluctuations in the external finance premium, private net worth, and the state of the economy.

To identify parameters governing the financial accelerator, we use multiple credit spreads and data on borrowing by nonfinancial businesses and households. Consistent with our definition of investment, which includes consumer durables and residential investment as well as business fixed investment, we relate the external finance premium to a weighted average of High Yield corporate bond and Asset-backed security spreads, where the weight each receives is derived from the shares of nonfinancial business and household debt in private credit taken from the Flow of Funds. To capture the impact of entrepreneurial leverage on financial conditions, we rely on the ratio of private credit to nominal GDP.

Forecasting Methodology

Constructing forecasts based on this model requires us to assign values to its many parameters. We do so using Bayesian methods to update an uninformative prior with data from 1989:Q2 through 2011:Q4. All of our forecasts condition on the parameters equaling their values at the resulting posterior's mode. These parameter values together with the data yield a posterior distribution of the economy's state in the final sample quarter.

In addition, we specify a sample break in our model that begins in 2008:Q1. At this point, we calibrate three parameters and re-estimate the parameters governing the decomposition of the current policy and forward guidance factors on the remaining sample. The three parameters we calibrate effect a structural break in the persistence of the *discount shock* which affects households' rate of time preference, the variance of the *inflation anchor shock*, and in the output gap coefficient in the Taylor rule.

Increasing the persistence of the shock to the discount rate captures the idea that deleveraging by households following a financial crisis is unusually slow. Its value in the second half of our sample period raises its half life from a little over half a year in the pre-crisis sample to more than three years in the second half of our sample. Similarly, lowering the variance of the inflation anchor shock reflects the fact that inflation expectations exhibit a downward trend in the early part of our sample, but have fluctuated considerably less since.

In the second half of our sample period, we also work with a coefficient on the output gap in our policy rule that is three times larger than its pre-crisis estimate. Our motivation for doing so is that the FOMC's policy response to the recent downturn in activity was more aggressive than in previous recessions in our sample, each of which was moderate by historical standards. Furthermore, in combination with the above, this assumption increases the likelihood that the zero lower bound on the federal funds rate is binding at any given date.

Table 1 presents data through 2012Q3 and forecasts for the following three years.

Table 1. Model Forecasts Q4 over Q4

	2011	2012	2013	2014	2015
Real GDP	2.0	1.6	3.2	3.3	3.2
Federal Funds Rate	0.1	0.1	0.1	0.3	0.8
Core PCE Inflation	1.7	1.7	0.9	0.6	0.9
Consumption	2.7	1.9	2.1	2.3	2.3
Investment	7.5	5.2	5.5	6.2	5.9
Gap in Rule	-7.6	-5.5	-3.8	-2.2	-1.1

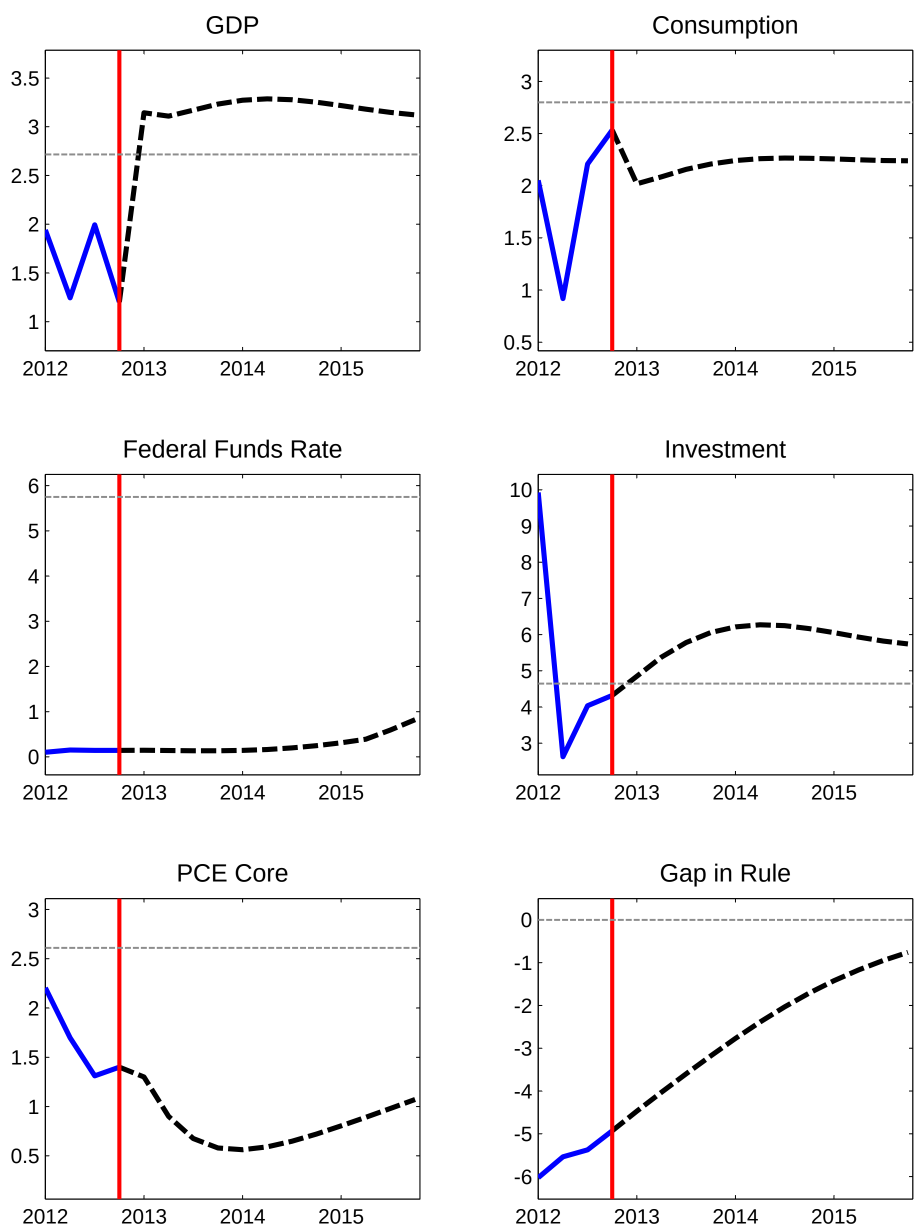
The first three rows correspond to three key macroeconomic observables, Real GDP growth (Q4-over-Q4), the Federal Funds Rate (Q4 average), and growth of the Core PCE deflator (Q4-over-Q4). The following rows report forecasts of Q4-over-Q4 growth for three model-defined aggregates of importance: Consumption of nondurable goods and non housing services, Investment in durable goods, residential housing, and business equipment and structures, and the measure of the output gap that enters our Taylor-type policy rule.

Figure 1 complements this with quarter-by-quarter data and forecasts of each of these series. The plots' dashed grey lines indicate the series' long-run values. The economy's long-run GDP growth rate – which we identify with potential growth – equals 2.7 percent.

The economy grows roughly 1 percent below potential in 2012 and then just above potential throughout the remainder of the forecast horizon. Consequently, the measure of the output gap that enters our Taylor-type policy rule continues to suggest a sizeable shortfall of output from potential, although it decreases from -5.5 to -1.1 percent over the forecast horizon.

Adverse demand shocks largely explain the recent weakness in the recovery of economic activity. In particular, a residual shock to the national income and product accounting identity, embodying a change in the valuation of inventories, net exports, and government expenditures in the model, accounts for much of the recent weakness in GDP growth. Negative serial correlation in

Figure 1: Forecasts starting 2013Q1



this shock then results in a slight boost to GDP growth in 2013 and 2014. Recent adverse technology shocks partially offset this.

The forecasted path for core PCE inflation is well below the model's long-run expected inflation rate of 2.6 percent, peaking at 1.7 percent in 2012 before receding below 1 percent and remaining there throughout the remainder of the forecast horizon. Positive *price mark-up shocks* account for the higher rate of inflation projected in 2012, while recent negative *inflation drift shocks* inferred from the Q3 and Q4 SPF forecast for 10-year CPI inflation largely explain the subsequently subdued path for inflation.

Our forecast for the federal funds rate is informed by futures prices which hold the funds rate below 0.5 percent through mid-2015. Thereafter, the forecast rate begins to rise as the conventional Taylor rule dynamics take over, increasing to 0.8 percent by the end of 2015. The expected output and inflation gaps are weak enough to merit only the gradual removal of policy accommodation. The increase in the funds rate in 2015 instead largely reflects mean reversion in our estimated interest rate rule.

Shock Decompositions

Our analysis identifies the structural shocks responsible for past fluctuations. To summarize this information, we follow a suggestion of Charlie Evans: Fix an object to be forecast, such as Q4-over-Q4 real GDP growth. Then, pick a date in the past and forecast the object conditional on the information as of that date. This is *not* a real-time forecast, because it uses revised data. The model can be used to decompose the associated forecast error into structural shocks. (A detailed explanation of the forecast error decomposition procedure begins below on page 33.) We repeatedly advance the forecast date, decompose the forecast error, and finally plot the results. In total, the model features eleven structural shocks and sixteen idiosyncratic disturbances without structural interpretations. For parsimony's sake, we group the shocks according to the following taxonomy.

Demand These are the structural non-policy shocks that move output and consumption-based inflation in the same direction. The model features four of them. One changes the households' rate of time discount. We call this the Discount shock. The next two are financial disturbances. The Spread shock generates fluctuations in the external finance premium beyond the level warranted by current economic conditions, and the Net Worth shock generates exogenous fluctuations in private balance sheets. Finally, this category also includes a shock to the sum of government expenditures, net exports, and changes in the valuation of inventories.

Supply Five shocks move real GDP and consumption-based inflation in opposite directions on impact. These *supply shocks* directly change

- Neutral Technology,
- Investment-Specific/Capital-Embodied Technology,
- Markups of Intermediate Goods Producers,
- Markups of Labor Unions, and
- Households' Disutility from Labor

The shock to households' disutility from labor is assumed to follow an ARMA(1,1) process, which is a parsimonious way of addressing low frequency movements in per capita hours worked and high frequency variation in wages.

Policy The model's monetary policy follows a Taylor rule with interest-rate smoothing, a time varying intercept, and a factor structure which identifies a Current Policy factor and a Forward Guidance factor. The time varying intercept, or Inflation Anchor shock, is disciplined by equating model-based average expected consumer price inflation to a measure of long-term inflation expectations taken from the Survey of Professional Forecasters. The Current Policy shock and Forward Guidance factor are derived from contemporaneous federal funds futures prices zero to four quarters before they affect the federal funds rate. In the second half of the sample, we extend the number of futures contracts so as to capture developments which affect the federal funds rate up to ten quarters ahead.

Residual We group the remaining shocks into a residual category. These include the idiosyncratic, that is series specific, shocks to the various price measures and monetary policy signals based on their factor structures, as well as the measurement errors in the interest rate spread and private credit-to-GDP ratio we use to capture the external finance premium and entrepreneurial net worth.

Table 2 reports the fraction of business-cycle variance attributable to shocks in each category for five key variables, the level of Real GDP, Real Consumption, and Real Investment, and the Federal Funds Rate and Core PCE Inflation. As already mentioned, we introduce an unanticipated sample break in 2008:Q1 and hence report decompositions for both sub-samples. Demand shocks dominate business cycles. This is particulary true in the second half of our sample. Monetary policy shocks make only a minor contribution in the earlier sample period, but explain almost one-third of GDP's total business cycle variance in the later period, due largely to their effect on Investment.

Inflation fluctuations are dominated by supply shocks in the early part of the sample, with exogenous shocks to intermediate goods' markups almost entirely accounting for supply shocks' 63 percent contribution. In contrast, supply shocks account for between 7 and 12 percent of GDP's total business-cycle variance depending on the sample period. The accounting for the Federal Funds Rate's variance is also very sample-dependent. In the second half of the sample, demand shocks are the key driver, while policy shocks dominate in the earlier period. Perhaps this is unsurprising, considering that we classify the shock that directly moves households' rate of time preference as "demand," and increase the activity coefficient in our interest rate rule post-2007.

Table 2. The Model's Decomposition of Business-Cycle Variance

1989:Q2-2007:Q4

	Demand	Supply	Policy	Residual
Real GDP	0.73	0.12	0.12	0.02
Federal Funds Rate	0.20	0.04	0.77	0.00
PCE Core	0.15	0.63	0.13	0.09
Consumption	0.88	0.08	0.03	0.01
Investment	0.88	0.04	0.08	0.00

2008:Q1-2011:Q4

	Demand	Supply	Policy	Residual
Real GDP	0.62	0.07	0.31	0.01
Federal Funds Rate	0.78	0.01	0.21	0.00
PCE Core	0.95	0.03	0.01	0.01
Consumption	0.96	0.02	0.03	0.00
Investment	0.61	0.04	0.34	0.00

Note: For each variable, the table lists the fraction of variance at frequencies between 6 and 32 quarters attributable to shocks in the listed categories. The numbers may not add to one due to rounding.

The Model's Specification and Estimation

Our empirical work uses eighteen variables, measured from 1989:Q2 through the present:

- Growth of nominal per capita GDP,
- Growth of nominal per capita consumption, which sums Personal Consumption Expenditures on Nondurable Goods and Services;
- Growth of nominal per capita investment; which sums Business Fixed Investment, Residential Investment, and Personal Consumption Expenditures on Durable Goods
- Per capita hours worked in Nonfarm Business,

- Growth of nominal compensation per hour worked in Nonfarm Business,
- Growth of the implicit deflator for GDP,
- Growth of the implicit deflator for consumption, as defined above,
- Growth of the implicit deflator for investment, as defined above,
- Growth of the implicit deflator for core PCE,
- Growth of the implicit deflator for core CPI,
- The interest rate on Federal Funds,
- Ten-year ahead CPI forecasts from the Survey of Professional Forecasters,
- A weighted average of High-Yield corporate and Mortgage-backed bond spreads with the 10-year Treasury and an Asset-backed bond spread with the 5-year Treasury; where the weights equal the shares of nonfinancial business, household mortgage, and household consumer debt in private credit,
- Ratio of private credit-to-GDP; which sums household and nonfinancial business credit market debt outstanding and divides by nominal GDP,
- Quarterly averages of federal funds and Eurodollar futures contract rates one through four quarters ahead.

The ratio of private credit-to-GDP is detrended using the Hodrick-Prescott filter with smoothing parameter 1e5. We do not directly use data on government spending, net exports, or the change in the valuation of inventories. Their sum serves as a residual in the national income accounting identity. To construct series measured per capita, we used the civilian non-institutional population 16 years and older. To eliminate level shifts associated with the decennial census, we project that series onto a fourth-order polynomial in time.

Our model confronts these data within the arena of a standard linear state-space model. Given a vector of parameter values, θ, log-linearized equilibrium conditions yield a first-order autoregression for the vector of model state variables, ζ_t.

$$\begin{aligned} \zeta_t &= F(\theta)\zeta_{t-1} + \varepsilon_t \\ \varepsilon_t &\sim N(0, \Sigma(\theta)) \end{aligned}$$

Here, ε_t is a vector-valued innovation built from the model innovations described above. Many of its elements identically equal zero. Table 3 lists the elements of ζ_t. Habit puts lagged nondurable consumption into the list, and investment adjustment costs place lagged investment there. Rules for indexing prices and wages that cannot adjust freely require the state to include lags of inflation and technology growth. Financial frictions place lagged entrepreneurial borrowing and net worth in the state. The list includes the lagged policy rate because it appears in the Taylor rule.

Gather the date t values of the fourteen observable variables into the vector y_t. The model analogues to its elements can be calculated as linear functions of ζ_t and ζ_{t-1}. We suppose that the data equal these model series plus a vector of "errors" v_t.

$$\begin{aligned} y_t &= G(\theta)\zeta_t + H(\theta)\zeta_{t-1} + v_t \\ v_t &= \Lambda(\varphi)v_{t-1} + e_t \\ e_t &\sim N(0, D(\varphi)) \end{aligned}$$

Here, the vector φ parameterizes the stochastic process for v_t. In our application, the only non-zero elements of v_t correspond to the observation equations for the three consumption-based measures of inflation, the GDP deflator, and the spread and private credit-to-GDP measures. The idiosyncratic disturbances in inflation fit the high-frequency fluctuations in prices and thereby allow the price markup shocks to fluctuate more persistently. These errors evolve independently of each other. In this sense, we follow Boivin and Giannoni (2006)

Table 3. Model State Variables

Symbol	Description	Disappears without
C_{t-1}	Lagged Consumption	Habit-based Preferences
I_{t-1}	Lagged Investment	Investment Adjustment Costs
π^p_{t-1}	Lagged Price Inflation	Indexing "stuck" prices to lagged inflation
K_t	Stock of Installed Capital	
A_t	Hicks-Neutral Technology	
a_t	Growth rate of A_t	Autoregressive growth of A_t
a_{t-1}	Lagged Growth Rate of A_t	Indexing "stuck" wages to lagged labor productivity growth
Z_t	Investment-Specific Technology	
z_t	Growth rate of Z_t	Autoregressive growth of Z_t
z_{t-1}	Lagged Growth Rate of Z_t	Indexing "stuck" wages to lagged labor productivity growth
ϕ_t	Labor-Supply Shock	
b_t	Discount Rate Shock	
$\lambda_{w,t}$	Employment Aggregator's Elasticity of Substitution	Time-varying Wage Markups
$\lambda_{p,t}$	Intermediate Good Aggregator's Elasticity of Substitution	Time-varying Price Markups
B_t	Entrepreneurial Borrowing	Need for external finance
B_{t-1}	Lagged Borrowing	
N_t	Entrepreneurial Net Worth	Risk-neutral entrepreneurs
N_{t-1}	Lagged Net Worth	
ν_t	Spread Shock	
ς_t	Net Worth Shock	
g_t	Government Spending Share Shock	
R_{t-1}	Lagged Nominal Interest Rate	Interest-rate Smoothing
$\varepsilon_{R,t}$	Monetary Policy Shock	
$\pi^\star_t$	Inflation Drift Shock	

by making the model errors "idiosyncratic". The other notable feature of the observation equations concerns the GDP deflator. We model its growth as a share-weighted average of the model's consumption and investment deflators.

Table 4 displays the estimated modes for a number of model parameters. We denote the sample of all data observed with Y and the parameters governing data generation with $\Theta = (\theta, \varphi)$. The prior density for Θ is $\Pi(\Theta)$, which resembles that employed by Justiniano, Primiceri, and Tambalotti (2011). Given Θ and a prior distribution for ζ_0, we can use the model solution and the observation equations to calculate the conditional density of Y, $F(Y|\Theta)$. To form the prior density of ζ_0, we apply the Kalman filter. The actual estimation begins with 1989:Q2. Bayes rule then yields the posterior density up to a factor of proportionality.

$$P(\Theta|Y) \propto F(Y|\Theta)\Pi(\Theta)$$

Beginning in 2008:Q1, we set the persistence of the discount shock at 0.95 and scale the variance of the inflation anchor shock to be one quarter and the coefficient on the output gap in the Taylor rule to be three times their earlier values. We re-estimate the volatility and factor loadings of the current policy and forward guidance factors and the standard deviations of the idiosyncratic shocks as well as the volatility of the discount shock. All remaining parameters are held fixed at their values in the first sub-sample. The Kalman filter is initialized with the necessary pre-sample data, and estimation on this second sample period proceeds as in the first except that as noted above we include signals up to ten quarters ahead in the estimation of the policy rule. We then calculate our forecasts with the model's parameter values set to this posterior distribution's mode.

Table 5 displays the estimate modes for both sample periods for the model parameters that are re-estimated on the second sub-sample.

Table 4. Selected Model Parameter Modes

Parameter	Description	Mode
ρ_π	Inflation anchor persistence	0.99
ρ_R	Inflation rate smoothing	0.85
ϕ_p	Inflation gap response	1.35
ϕ_y	Output gap response	0.10
α	Capital Share	0.17
δ	Depreciation rate	0.03
ι_p	Indexation Prices	0.08
ι_w	Indexation Wages	0.28
$\gamma_{\star 100}$	Steady state consumption growth	0.47
$\gamma_{\mu 100}$	Steady state investment-specific technology growth	0.60
$\mathcal{H}$	Habit	0.89
λ_p	Steady state price markup	0.10
π^{ss}	Steady state quarterly inflation	0.65
β	Steady state discount factor	0.997
$\mathcal{G}^{ss}$	Steady state residual expenditure share in GDP	0.22
ν	Inverse Frisch elasticity	2.17
κ_p	Price Phillip's curve slope	0.001
κ_w	Wage Phillip's curve slope	0.005
χ	Utilization elasticity	4.80
$\mathcal{S}$	Investment adjustment elasticity	7.84
$\frac{B}{N}$	Steady state borrowing to net worth ratio	1.11
$\mathcal{F}_{KN}$	Steady state spread	0.69
τ	Net worth elasticity	0.002
ζ	Entrepreneur survival probability	0.91
ρ_b	Discount factor persistence	0.76
ρ_υ	Spread persistence	0.99
ρ_ς	Net worth persistence	0.64
ρ_g	G + NX persistnce	0.99
ρ_z	Neutral technology growth persistence	0.10
ρ_μ	Investment technology growth persistence	0.73
ρ_{λ_p}	Price markup persistence	0.61
ρ_ψ	AR coefficient labor disutility	0.95
θ_ψ	MA coefficient labor disutility	0.98

Table 5. Selected Modes for Re-estimated Parameters

Parameter	Description	First Mode	Second Mode
σ_b	Std. dev. Discount factor shock	0.14	0.06
σ_{f1}	Std. dev. Current Policy factor	0.04	0.05
σ_{f2}	Std. dev. Forward Guidance factor	0.06	0.07
σ_{u1}	Std. dev. 1st idiosyncratic shock	0.04	0.05
σ_{u2}	Std. dev. 2nd idiosyncratic shock	0.02	0.03
σ_{u3}	Std. dev. 3rd idiosyncratic shock	0.02	0.03
σ_{u4}	Std. dev. 4th idiosyncratic shock	0.05	0.03
σ_{u5}	Std. dev. 5th idiosyncratic shock		0.02
σ_{u6}	Std. dev. 6th idiosyncratic shock		0.02
σ_{u7}	Std. dev. 7th idiosyncratic shock		0.02
σ_{u8}	Std. dev. 8th idiosyncratic shock		0.09
σ_{u9}	Std. dev. 9th idiosyncratic shock		0.09
σ_{u10}	Std. dev. 10th idiosyncratic shock		0.09
$\mathcal{A}_1$	Current 1	1.25	1.25
$\mathcal{A}_2$	Current 2	0.69	0.43
$\mathcal{A}_3$	Current 3	0.42	0.18
$\mathcal{A}_4$	Current 4	-0.21	0.08
$\mathcal{A}_5$	Current 5		-0.01
$\mathcal{A}_6$	Current 6		0.02
$\mathcal{A}_7$	Current 7		0.01
$\mathcal{A}_8$	Current 8		-0.01
$\mathcal{A}_9$	Current 9		-0.00
$\mathcal{A}_{10}$	Current 10		-0.02
$\mathcal{B}_1$	Lead 1	0.80	0.16
$\mathcal{B}_2$	Lead 2	1.00	0.55
$\mathcal{B}_3$	Lead 3	0.92	0.78
$\mathcal{B}_4$	Lead 4	0.43	1.03
$\mathcal{B}_5$	Lead 5		1.00
$\mathcal{B}_6$	Lead 6		1.09
$\mathcal{B}_7$	Lead 7		1.03
$\mathcal{B}_8$	Lead 8		1.05
$\mathcal{B}_9$	Lead 9		0.91
$\mathcal{B}_{10}$	Lead 10		0.98

Five Key Equations

This section summarizes the inferred parameters by reporting the estimates of five key equations: the two equations of the financial accelerator capturing the External Finance Premium and the evolution of private Net Worth, and the log-linearized forms of the Taylor Rule, the Price Phillips Curve, and the Wage Phillips Curve.

Financial Accelerator

Financial frictions in the model arise from imperfections in private financial intermediation due to lenders' costly state verification of the returns realized by entrepreneurs' projects. We introduce risk neutral entrepreneurs into the model who at the end of period t purchase capital goods, $\overline{K_t}$, from the capital installers at the price Q_t, using a mix of internal and external resources, given by end of period net worth, N_t, and borrowing B_t, such that $Q_t\overline{K_t} = N_t + B_t$.

In the next period, $t+1$, entrepreneurs optimally choose the rate of utilization, u_{t+1}, and rent the effective capital stock $K_{t+1} = u_{t+1}\overline{K_t}$ to the goods producing firms, receiving in return the gross rental rate of capital ω^k_{t+1}. At the end of period $t+1$ they resell the remaining capital stock, $(1-\delta)\overline{K_t}$ back to the capital producers at the price Q_{t+1}.

External Finance Premium

We assume that the external finance premium –the ratio of the equilibrium return to capital and the expected real interest rate– is an increasing function of the entrepreneurs' leverage ratio, $\frac{\overline{K_t}\,Q_t}{N_t}$, according to

$$\frac{E_t[1+r^k_{t+1}]}{E_t[\frac{1+R_t}{\pi_{t+1}}]} = F\left[\frac{\overline{K_t}\,Q_t}{N_t}\right]e^{\nu_t}$$

with R_t the nominal interest rate, π_{t+1} the gross inflation rate and $F(1) = 1$, $F' > 0, F'' > 0$.[1] The spread shock, e^{ν_t}, can be viewed as a disturbance to credit supply, moving the external finance premium beyond the level dictated by entrepreneurial net worth. We parameterize the steady state level of $\mathcal{F}_{KN}$ as well as its elasticity τ. We estimate the former to be 2.76 and the latter to be pretty small. The annualized steady state external finance premium is estimated to be 2.98 percent.

Net Worth

The law of motion for entrepreneurial net worth is given by

$$N_t = 0.91\left\{\overline{K}_{t-1}Q_{t-1}[1+r_t^k] - E_{t-1}[1+r_{t-1}^k]B_{t-1}\right\} + 0.09\Gamma_t + \varsigma_t$$

where Γ_t is the transfer from exiting to new entrepreneurs and ς_t is a shock to net worth that can arise for instance from time-varying survival probabilities for entrepreneurs. The AR(1) laws of motion for the spread and net worth shocks, ν_t and ς_t, are estimated to have independent autoregressive parameters $(0.99, 0.64)$ and volatilities i=$0.23, 0.37$.

Taylor Rule

$$R_t = 0.85R_{t-1} + 0.32\left(1.34\left(\frac{1}{4}\sum_{j=-1}^{2} E_t(\pi_{t+j}) - \pi_t^{\star}\right) + 0.11\left(\frac{1}{4}\sum_{j=-1}^{2} E_t(\hat{x}_{t+j})\right)\right) + \sum_{j=0}^{M}\xi_{t-j,j}$$

$$[1+\lambda(1-L)^2(1-F)^2]\hat{x}_t = \lambda(1-L)^2(1-F)^2\hat{y}_t$$

$$\xi_{t,j} = \mathcal{A}_j f_t^c + \mathcal{B}_j f_t^F + u_{t,j}$$

[1] Notice that that if entrepreneurs are self-financed, which we rule out in steady state, $F(1) = 1$ and there is no external finance premium.

Besides the lagged interest rate, the variables appearing on the right-hand side of our interest rate rule are an inflation gap, an output gap, and current and future deviations from the systematic component of the rule. For any variable v, $\hat{v}$ denotes deviations from steady state.

The inflation gap is the deviation of a four quarter average of model inflation from the time-varying inflation drift, or anchor, π_t^* which varies exogenously according to an AR(1) process. The four quarter moving average of inflation includes both lagged, current, and future values of inflation. The monetary authority uses the structure of the model to forecast the future terms.

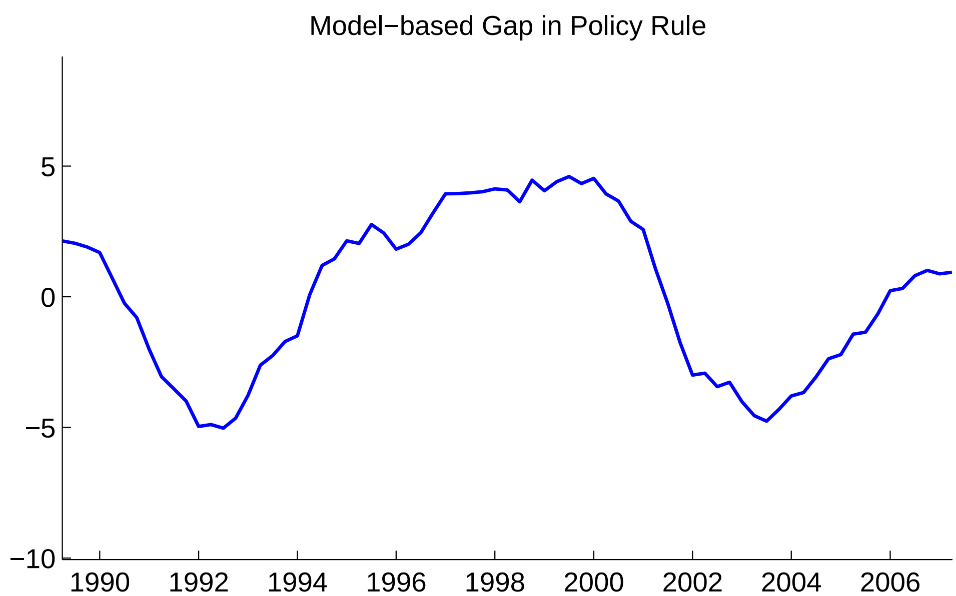
The inflation drift term can be interpreted in the context of the model as the monetary authority's medium-run desired rate of inflation. It is perfectly credible in the sense that we equate model-based average expected consumer price inflation over the next forty quarters to the ten-year ahead CPI forecast from the Survey of Professional Forecasters.

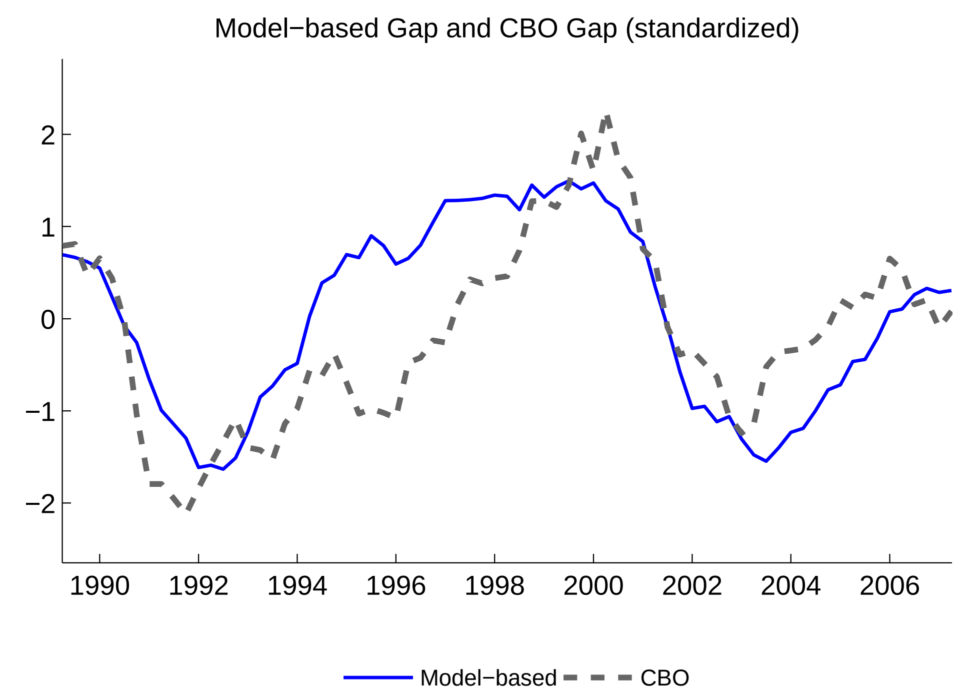
We define the output gap as the four-quarter moving average of detrended model output. Following Curdia, Ferrero, Ng, and Tambalotti (2011), the detrending is model-based where L and F represent the lag and lead operators and λ is a smoothing parameter that we estimate to be 9104. The filter above approximates the Hodrick-Prescott filter. While the methodologies differ, figure 2 demonstrates that our output gap also compares well with the CBO's output gap measure from 1989:Q2-2007:Q2.

Holding the economy's growth rate fixed, the long-run response of R_t to a permanent one-percent increase in inflation is 1.3 percent. Thus, the model satisfies the Taylor principle. Our estimated coefficient of the output response to our rule is 0.1. We scale this coefficient by a factor of 3 in the second half of our sample.

Monetary policy shocks have a factor structure such that the factors f_t^c and f_t^F represent the *i.i.d. current policy shock* and the *forward guidance factor*. The disturbances $u_{t,j}$ are assumed uncorrelated across both j and t, and the factor

Figure 2. The Output Gap





structure identified by restricting the loading matrices, $\mathcal{A}$ and $\mathcal{B}$, such that the forward guidance factor only influences future values of the federal funds rate. Figure 3 depicts our estimates of both factors from 1989:Q2-2007:Q2.

By including forward looking terms for the inflation and output gaps in the interest rate rule, we account for news about both up to two quarters ahead from our forward guidance shocks. We estimate both the current policy and forward guidance factors using contemporaneous data on the federal funds rate and federal funds and Eurodollar futures contract prices. In the first sub-sample, this includes futures contracts one to four quarters ahead; while in the second sub-sample, we use futures contracts one to ten quarters ahead.

Historical decompositions highlighting the role played by forward guidance shocks for per capita GDP, core PCE inflation, and the federal funds rate from 1989:Q2-2007:Q2 are shown in figures, 4, 5, and 6. Forward guidance played a role in explaining each during the 1993-1995 and 2002-2004 periods as detailed in Campbell, Fisher, and Justiniano (2012). The first episode can be linked to statements by Chairman Greenspan extending expectations for increases in the funds rate, while the second is closely related to the extended period of low rates that followed 9/11.

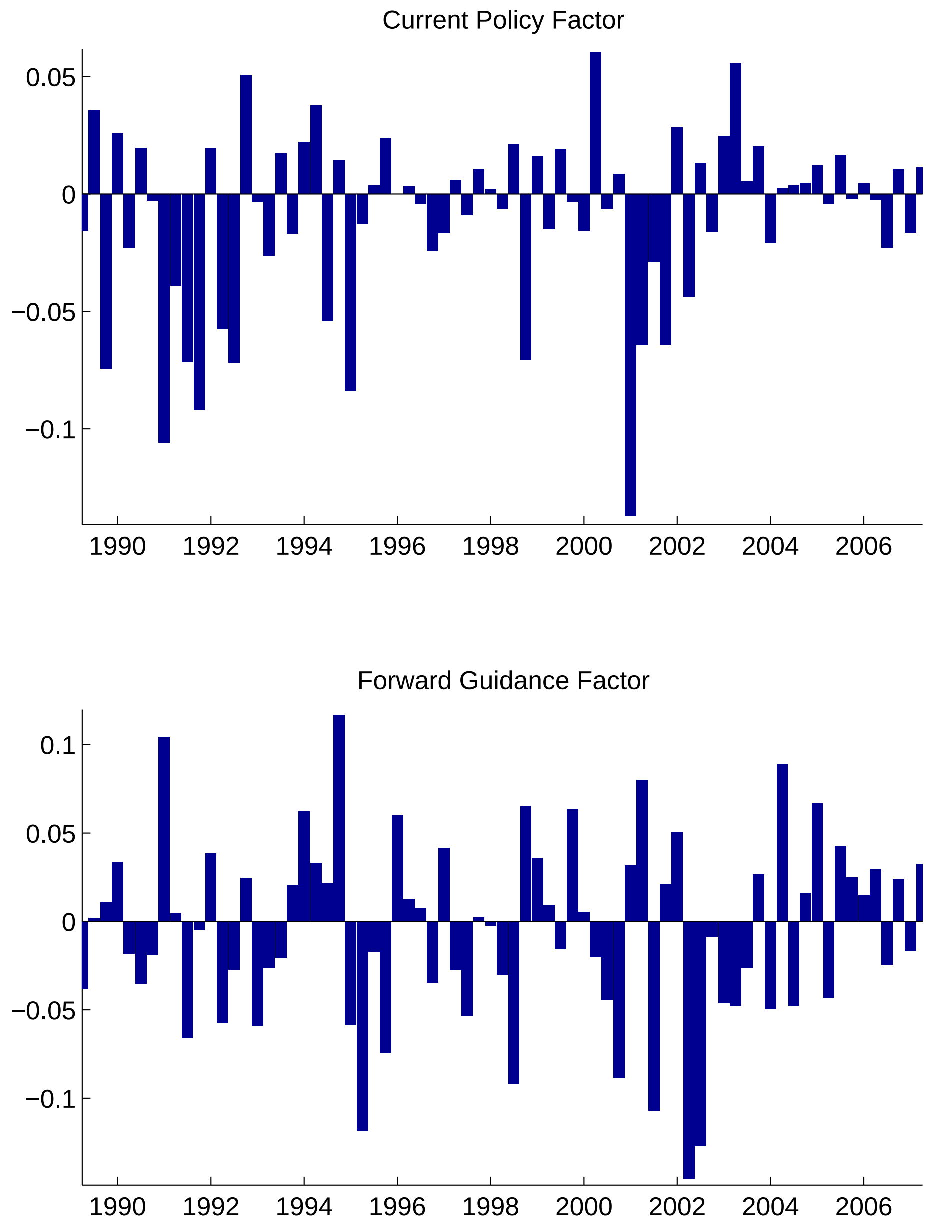
Price Phillips Curve

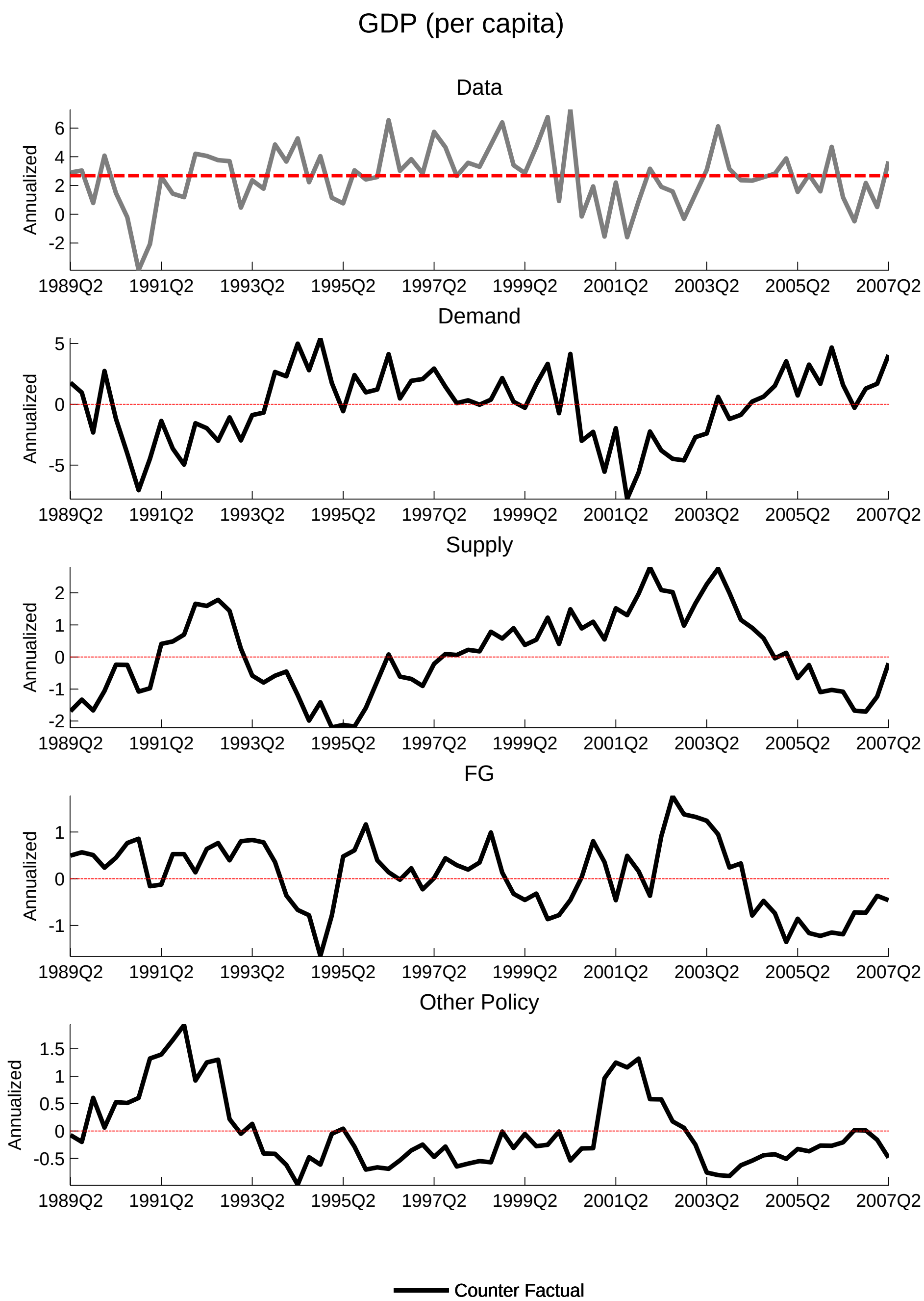
$$\pi_t^p = 0.923 E_t \pi_{t+1}^p + 0.074 \pi_{t-1}^p + 0.002 s_t + \epsilon_t^p$$

Here, s_t represents intermediate goods producers' common marginal cost. The introduction of inflation drift does not alter the dynamic component of inflation indexation which is linked to the previous quarter's inflation rate.

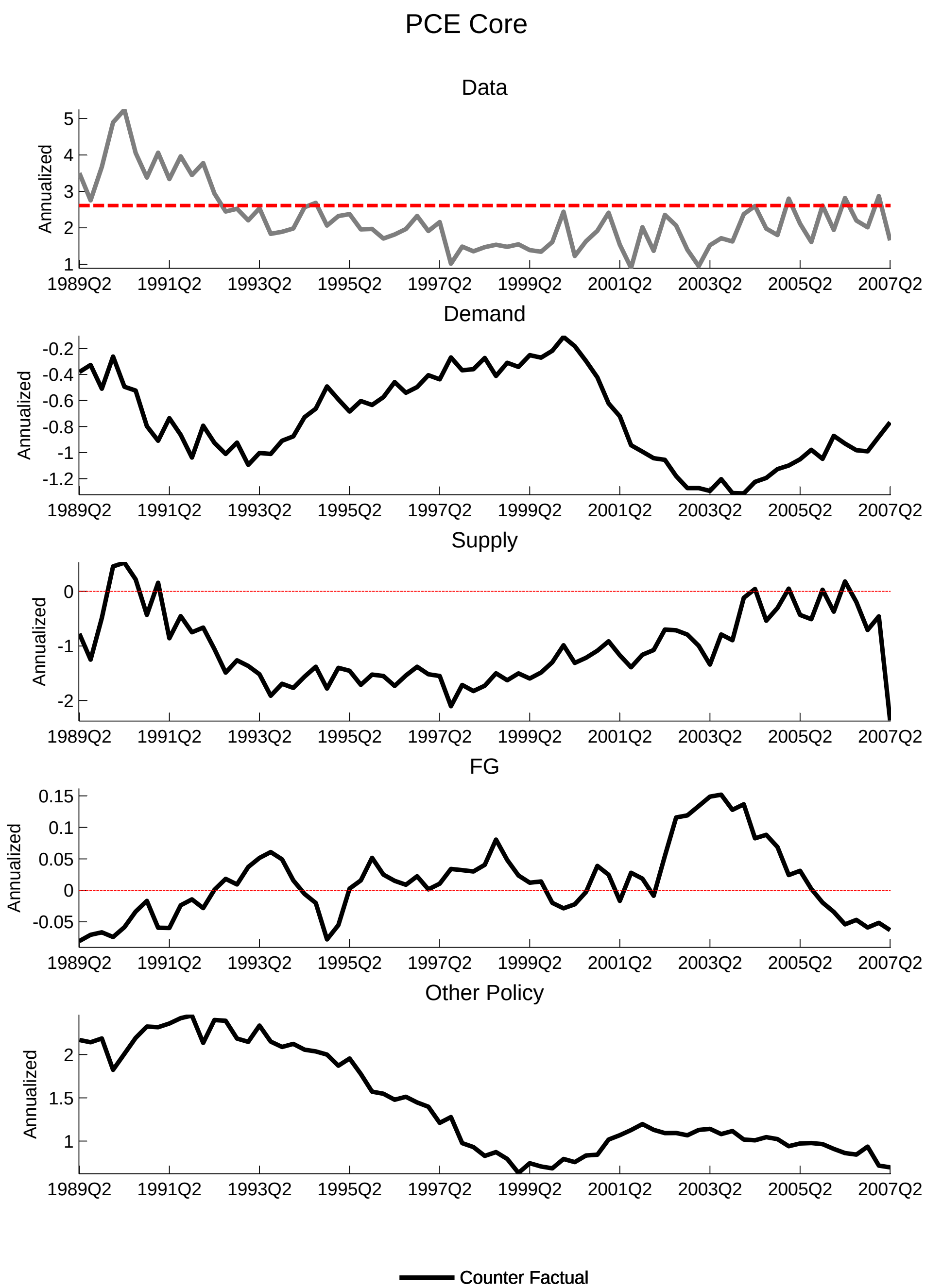
- The slope of the estimated Phillips Curve is considerably flat compared to some other estimates in the literature. This reflects at least in part our sample period which starts in 1989.

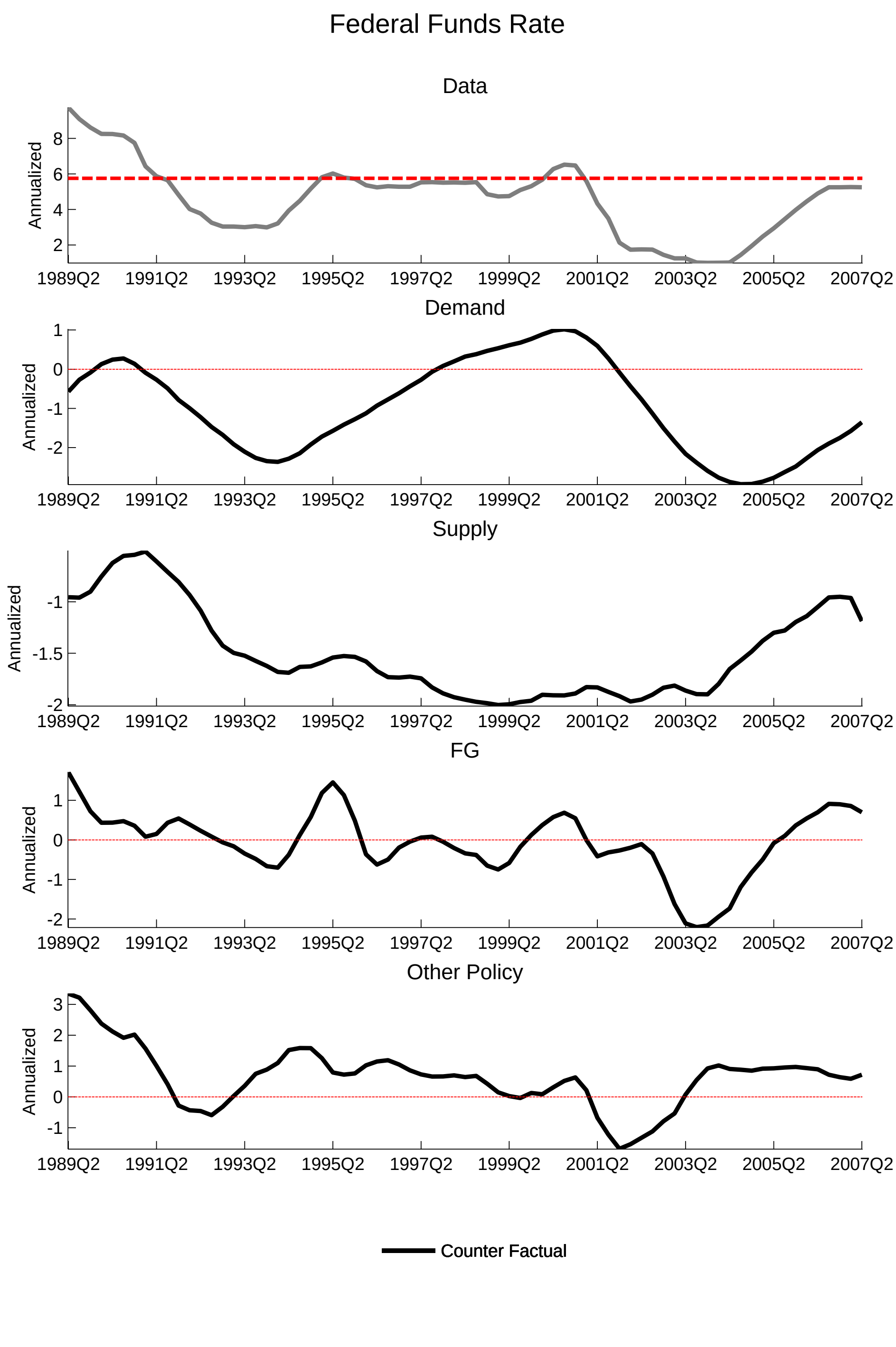
Figure 3. Current Policy and Forward Guidance Factors





GDP (per capita)
Data
Annualized
6
4
2
0
-2
1989Q2
1991Q2
1993Q2
1995Q2
1997Q2
1999Q2
2001Q2
2003Q2
2005Q2
2007Q2
Demand
5
0
-5
Supply
2
1
0
-1
-2
FG
1
0
-1
Other Policy
1.5
1
0.5
0
-0.5
Counter Factual


PCE Core
Data
Demand
Supply
FG
Other Policy
Annualized
1989Q2
1991Q2
1993Q2
1995Q2
1997Q2
1999Q2
2001Q2
2003Q2
2005Q2
2007Q2
Counter Factual


Federal Funds Rate
Data
Annualized
2
4
6
8
1989Q2
1991Q2
1993Q2
1995Q2
1997Q2
1999Q2
2001Q2
2003Q2
2005Q2
2007Q2
Demand
Annualized
1
0
-1
-2
Supply
Annualized
-1
-1.5
-2
FG
Annualized
1
0
-1
-2
Other Policy
Annualized
3
2
1
0
-1
Counter Factual

- Producers unable to update their price with all current information are allowed to index their prices to a convex combination of last quarter's inflation rate with the steady-state inflation rate. This places π^p_{t-1} in the Phillips curve. The estimated weight on steady-state inflation is 0.92.

Wage Phillips Curve

The Wage Phillips curve can be written as

$$\pi^w_t+\pi^p_t+j_t-\iota_w\left(\pi^p_{t-1}+j_{t-1}\right)=\beta E_t\left[\pi^w_{t+1}+\pi^p_{t+1}+j_{t+1}-\iota_w\left(\pi^p_t+j_t\right)\right]+\kappa_w x_t+\epsilon^w_t,$$

where π^w_t and π^p_t correspond to inflation in real wages and consumption prices respectively, $j_t = z_t + \frac{\alpha}{1-\alpha}\mu_t$ is the economy's technologically determined stochastic trend growth rate, with α equal to capital's share in the production function, z_t the growth rate of neutral technology, and μ_t the growth rate of investment-specific technical change. The term $\pi^p_{t-1} + z_{t-1} + j_t$ arises from indexation of wages to a weighted average of last quarter's productivity-adjusted price inflation and its steady state value. The estimated weight on the steady state equals 0.72. The log-linearized expression for the ratio of the marginal disutility of labor, expressed in consumption units, to the real wage is

$$x_t = b_t + \psi_t + \nu l_t - \lambda_t - w_t,$$

where b_t and ψ_t are disturbances to the discount factor and the disutility of working, respectively, l_t hours, λ_t the marginal utility of consumption and w_t the real wage. Finally, ϵ^w_t is a white noise wage markup shock.

Note that without indexation of wages to trend productivity, this equation says that nominal wage inflation (adjusted by trend growth) depends positively on future nominal wage inflation (also appropriately trend-adjusted), and increases in the disutility of the labor-real wage gap.

The estimated equation is given by

$$\pi^w_t+\pi^p_t+j_t-0.28\left(\pi^p_{t-1}+j_{t-1}\right)=0.997\times E_t[\pi^w_{t+1}+\pi^p_{t+1}+j_{t+1}-0.28\left(\pi^p_t+j_t\right)]+0.01x_t+\epsilon^w_t,$$

The Model's Shocks

The following shocks figure prominently into explaining the structure of the model: The discount rate shock, the spread shock to the external finance premium, the neutral technology shock, the price mark-up shock, the monetary policy (current and forward guidance factor) and inflation anchor shocks. In this section, we provide greater detail on the model's responses to these seven shocks by presenting impulse response functions to a one standard deviation realization of each of these disturbances.

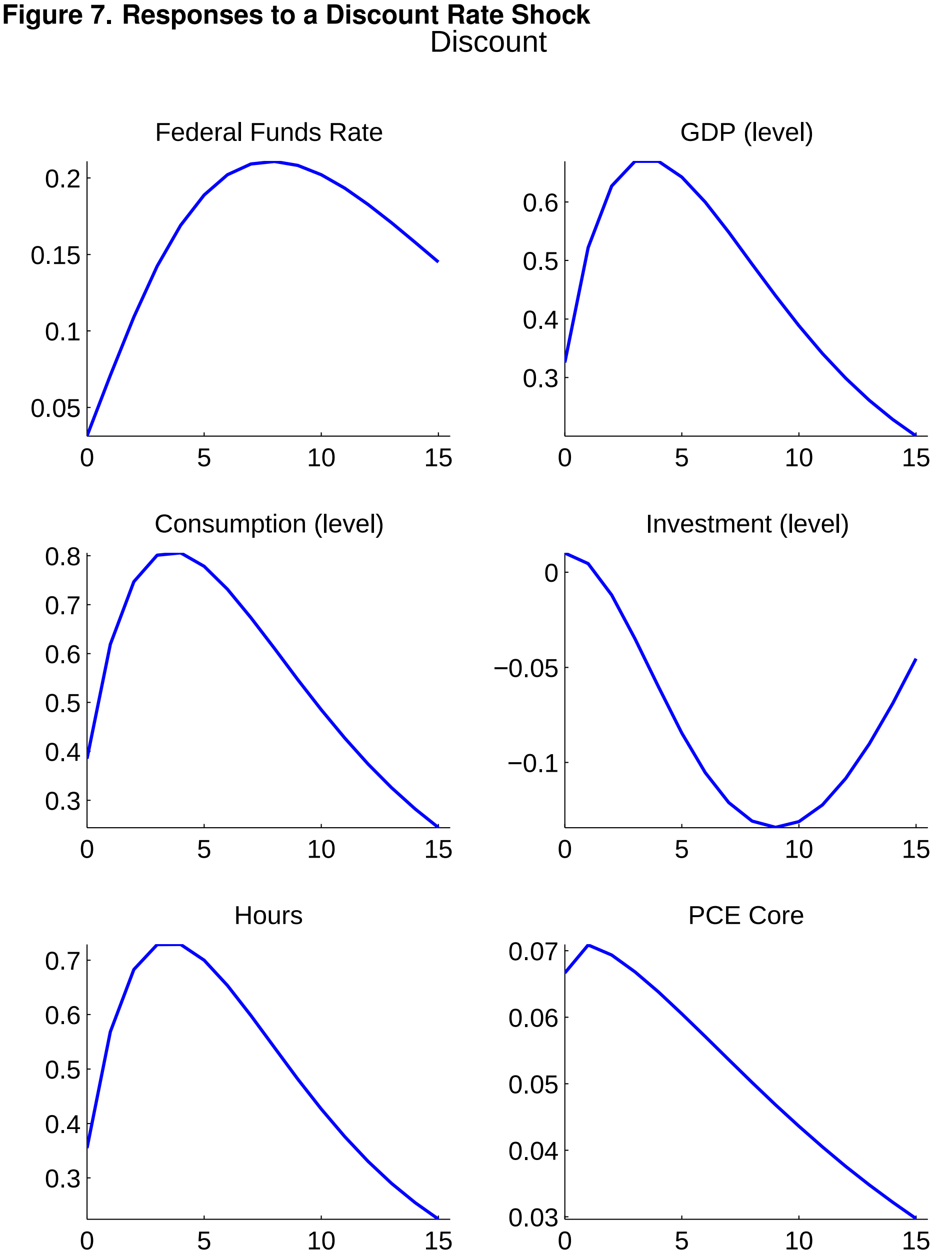
Figure 7 plots responses to a discount rate shock that increases impatience and tilts desired consumption profiles towards the present. The variables examined are real GDP, the federal funds rate, consumption, investment, inflation, and hours worked.

In a neoclassical economy, this shock would be contractionary on impact. Upon becoming more impatient, the representative household would increase consumption and decrease hours worked. To the extent that the production technology is concave, interest rates and real wages would rise; and regardless of the production technology both real GDP and investment would drop.

Increasing impatience instead *expands* activity in this New Keynesian economy. As in the neoclassical case, consumption rises on impact. However, investment remains unchanged as adjustment costs penalize the sharp contraction of investment from the neoclassical model. Instead, investment displays a hump-shaped response, exhibiting negative co-movement with consumption with a slight lag. Habit causes the consumption growth to persist for two more quarters before it begins to decline. Market clearing requires either a rise of the interest rate (to choke off the desired consumption expansion) or an expansion of GDP. By construction, the Taylor rule prevents the interest rate from rising unless the shock is inflationary or expansionary. Therefore, GDP must rise. This in turn requires hours worked to increase.

Two model features overcome the neoclassical desire for more leisure. First,

Figure 7. Responses to a Discount Rate Shock



some of the labor variants' wages are sticky. For those, the household is obligated to supply whatever hours firms demand. Second, the additional labor demand raises the wages of labor variants with wage-setting opportunities. This rise in wages pushes marginal cost up and lies behind the short-run increase in inflation. After inflation has persisted for a few quarters, monetary policy tightens and real rates rise.

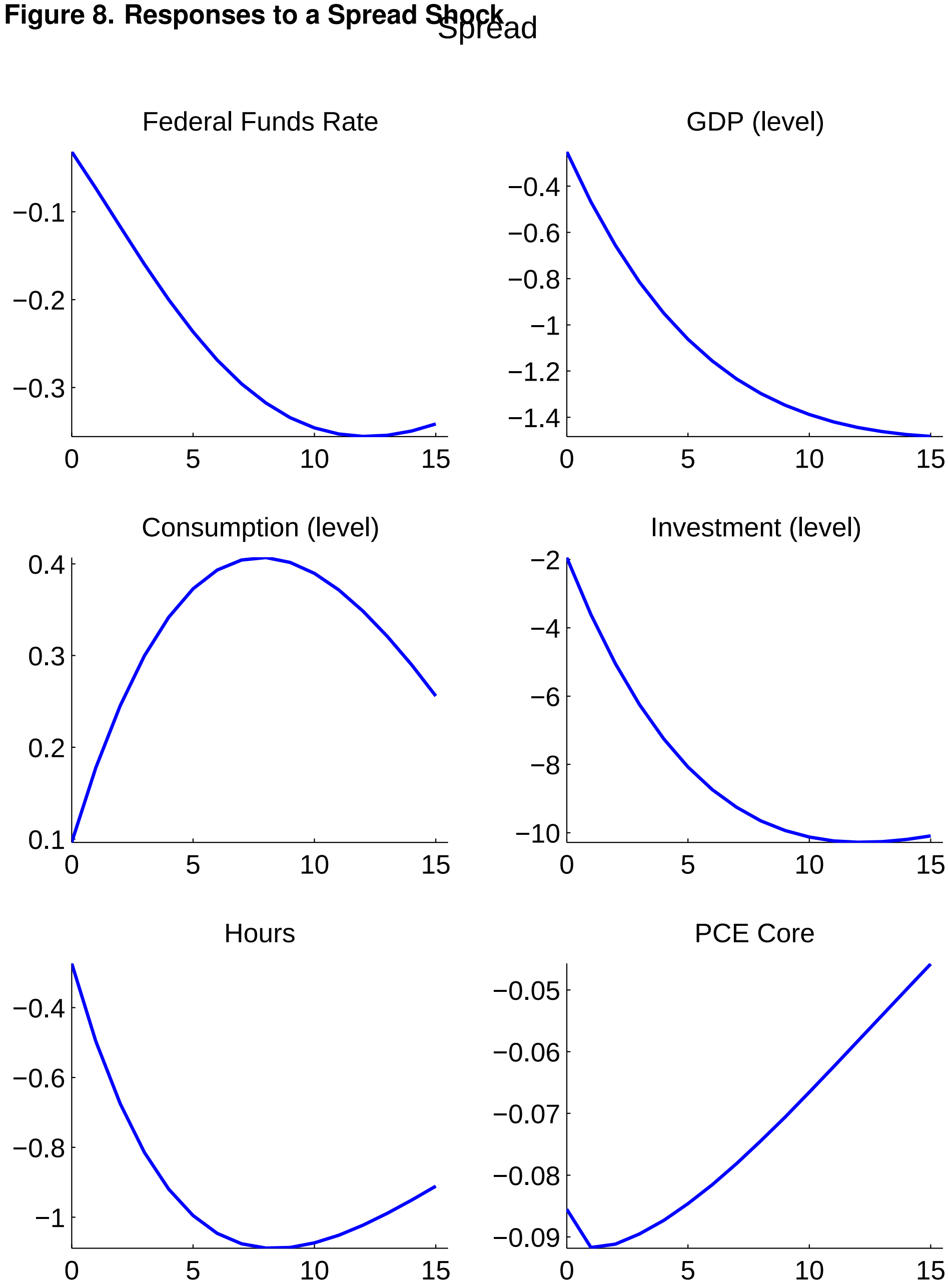
Since the discount rate shock moves output and prices in the same direction, a Keynesian analysis would label it a shift in "demand." In the neoclassical sense, it is also a demand shock, albeit a reduction in the demand for future goods. The matching neoclassical supply shock in our model is to the spread shock. A positive shock to it decreases the supply of future goods. Figure 8 plots the responses to such a shock.[2]

A positive spread shock reduces the supply of credit available to entrepreneurs, who are then forced to shrink their demand for capital. The price of installed capital drops sharply so that the return to capital collapses on impact and is followed by a prolonged contraction in borrowing by entrepreneurs. The decline in borrowing is initially smaller than in net worth, which results in a rising leverage ratio and a further tightening of the external finance premium. Investment and other measures of real activity, with the exception of consumption, all decline. In response to lower activity and inflation, monetary policy eases and real rates move lower.

Increasing the external finance premium thus lowers investment, hours worked, GDP, and the real interest rate. Two aspects of our model limit the response of consumption on the same shock's impact. First, habit-based preferences penalize an immediate increase in consumption. Second, monetary policy responds to the shock only slowly, so real interest rates are slow to adjust. Although this shock

[2]The interpretation of this shock is not unique. The negative spread shock resembles in nature a positive marginal efficiency of investment (MEI) shock. It could also be interpreted as a shock to the efficiency of channeling funds to entrepreneurs or, more broadly, variations in the supply of credit. Barro and King (1984) and Greenwood, Hercowitz, and Huffman (1988) consider the analogous responses to an MEI shock from a neoclassical model.

Figure 8. Responses to a Spread Shock



changes the economy's technology for intertemporal substitution – and therefore deserves the neoclassical label "supply" – it makes prices and output move in the same direction. For this reason, it falls into our Keynesian taxonomy's "demand" category.

Figure 9 displays the responses to a neutral technology shock. Measures of real activity, with the exception of hours, all rise after a positive technology shock. The effects are delayed, however, due to habit persistence in consumption and investment adjustment costs. As inflation declines on impact, monetary policy progressively eases over a period of 6 quarters before bringing real rates back to their steady-state as real activity picks up. This results in a hump-shaped response in GDP, consumption, and investment. Since the neutral technology shock moves output and prices in opposite directions, we label it a shift in "supply."

Figure 10 depicts the responses to a positive price mark-up shock. Inflation increases on impact and measures of real activity all decline, thereby resembling a transitory negative technology shock. Monetary policy tightens over a period of four quarters before real rates gradually return to their steady-state as real activity picks up.

Figures 11 and 12 present the impulse response functions for our two monetary policy shocks, the current policy and forward guidance factors. We begin with the forward guidance factor. A positive realization of this shock signals a hump-shaped increase in the interest rate given our estimated factor loadings with limited movement in the rate today. The gradual decline in the interest rate after four quarters is governed mostly by the autoregressive coefficient in the rule.

In response to the anticipated tightening, activity contracts immediately, afterward following a hump-shaped response. Inflation declines primarily on impact, as forward looking price setters incorporate the weaker outlook for activity into their decisions today. The current policy factor displays a similar pattern, except that compared with the forward guidance factor it accelerates the

Figure 9. Responses to a Neutral Technology Shock

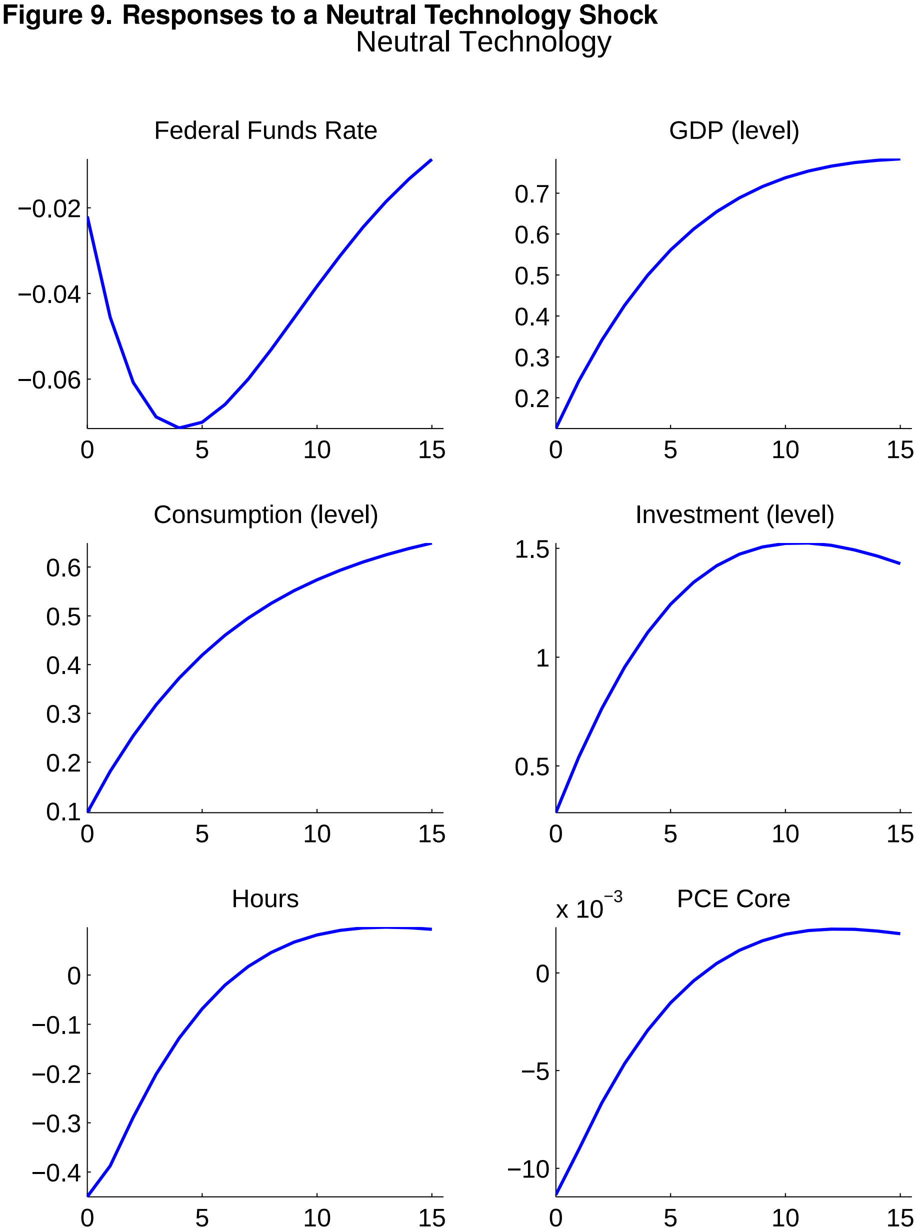
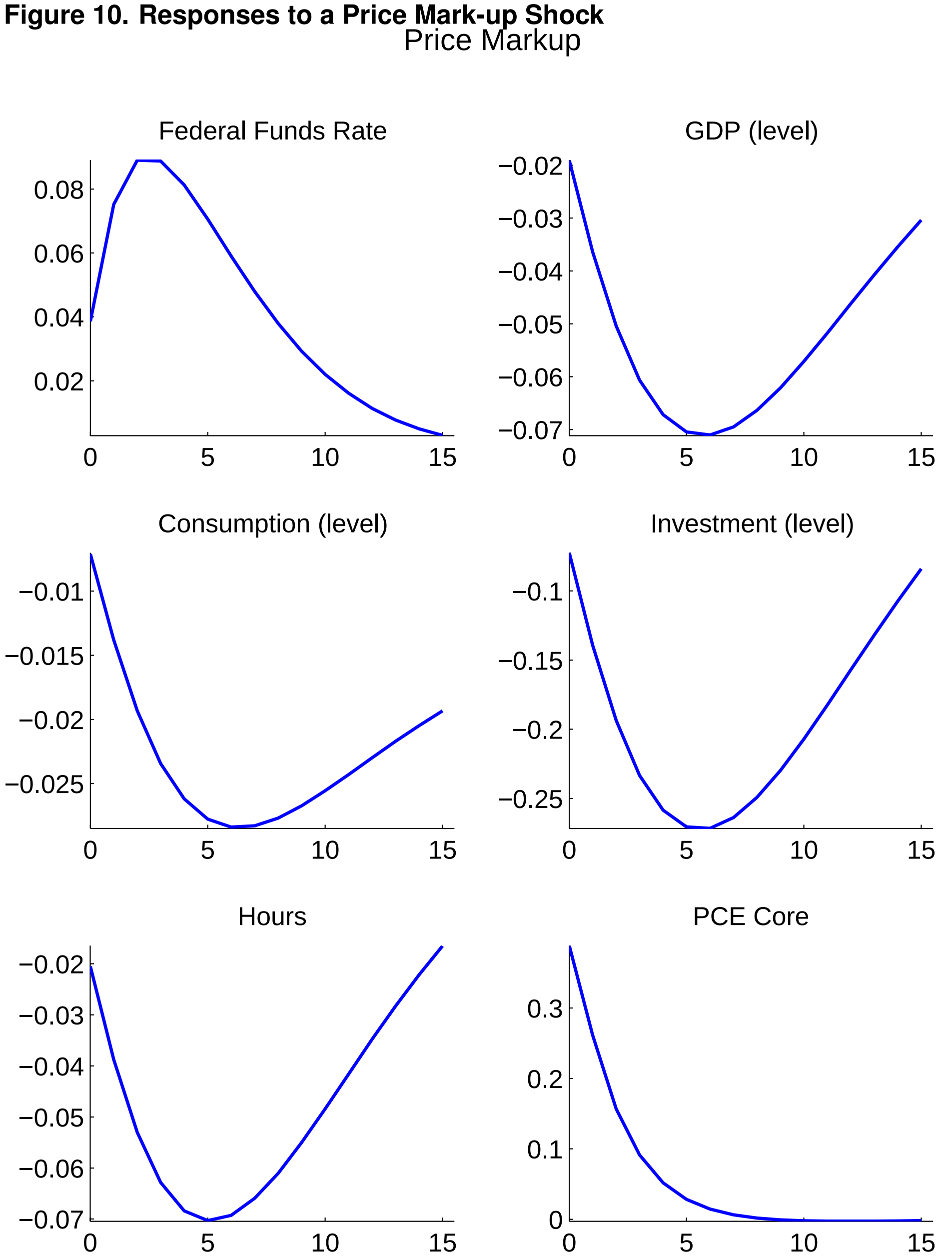


Figure 10. Responses to a Price Mark-up Shock



policy tightening. That is, it displays an immediate jump followed by a steeper rise and subsequent fall.

The responses to the current policy factor are standard, but those following a forward guidance shock require more explanation. At the announcement date, the expected value of the policy rate four quarters hence rises. Because both Phillips curves are forward looking, this expected contraction causes both prices and quantities to fall. This anticipated weakness then feeds through the Taylor rule to create a gradual *easing* of policy.

Figure 13 displays the impulse response functions for a positive inflation anchor shock. In response, inflation jumps on impact, as does expected long-run expected inflation (not shown). Under the assumption of perfect credibility, higher inflation is achieved without any contemporaneous movement in the federal funds rate. Although monetary policy does eventually tighten to return the real interest rate to its steady-state, lower real rates during the initial transition fuel an increase in consumption, investment, and hours. Therefore, GDP moves up as well. Given the high degree of persistence of this shock, its effects on real activity and inflation dissipate at a glacial pace.

Shock Decomposition Methodology

We credit Charles Evans with the original ideas behind this decomposition. For the shock decomposition, we set the model's parameters to their values at the posterior distribution's mode, $\hat{\theta}$. Using *all* available data we use the Kalman smoother to extract sequences of estimated states $\{\hat{\zeta}_t\}_{t=1}^T$ and a innovations $\{\hat{\varepsilon}_t\}_{t=1}^T$. By construction, these satisfy the estimated transition equation for the state.

$$\hat{\zeta}_t = F(\hat{\theta})\hat{\zeta}_{t-1} + \hat{\varepsilon}_t,$$

To keep this discussion simple, we henceforth suppose that the "error" shocks in v_t equal zero. Incorporating them into the analysis changes the actual calculations only little.

Figure 11. Responses to the Current Policy Factor

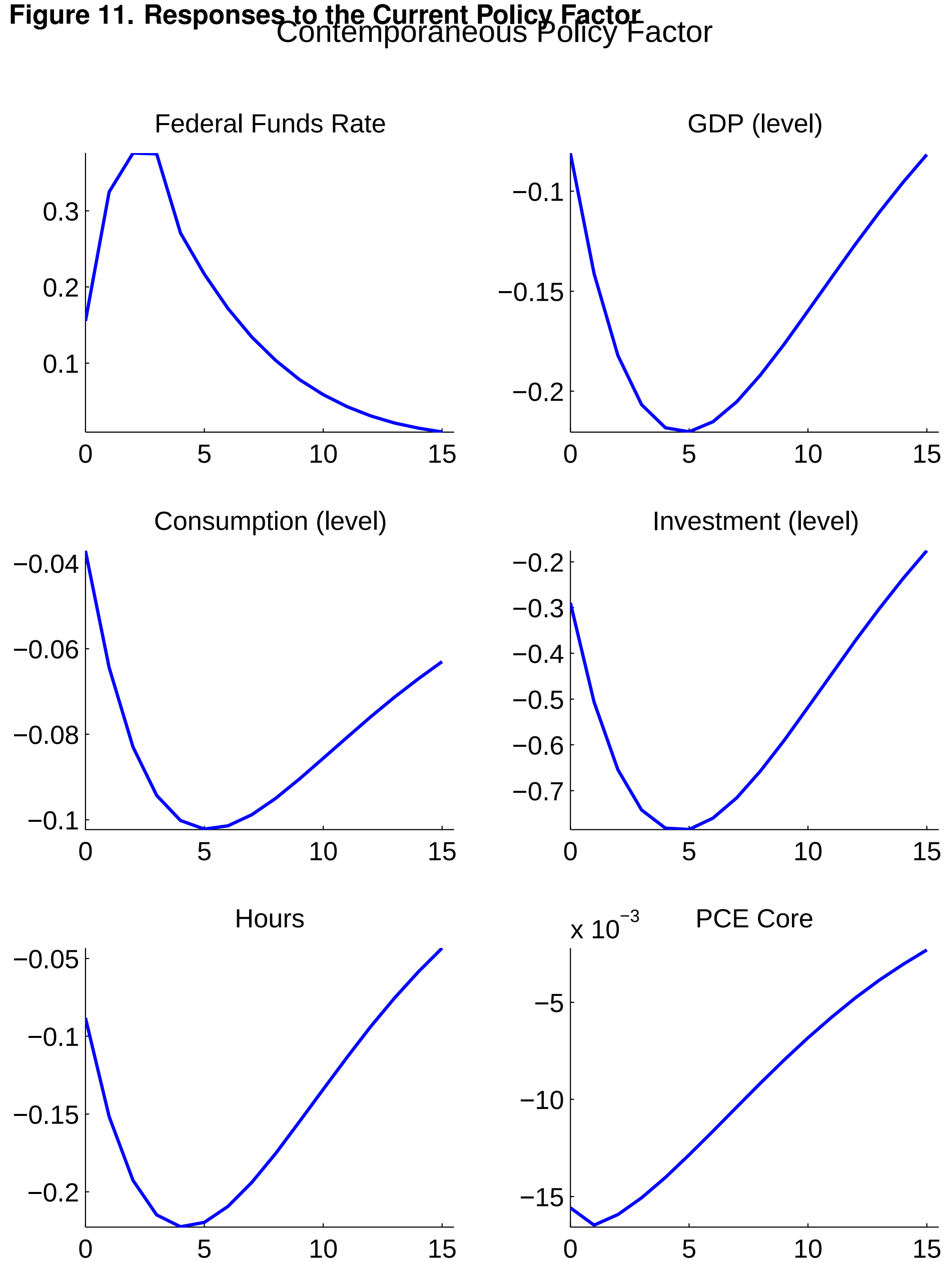


Figure 12. Responses to the Forward Guidance Factor

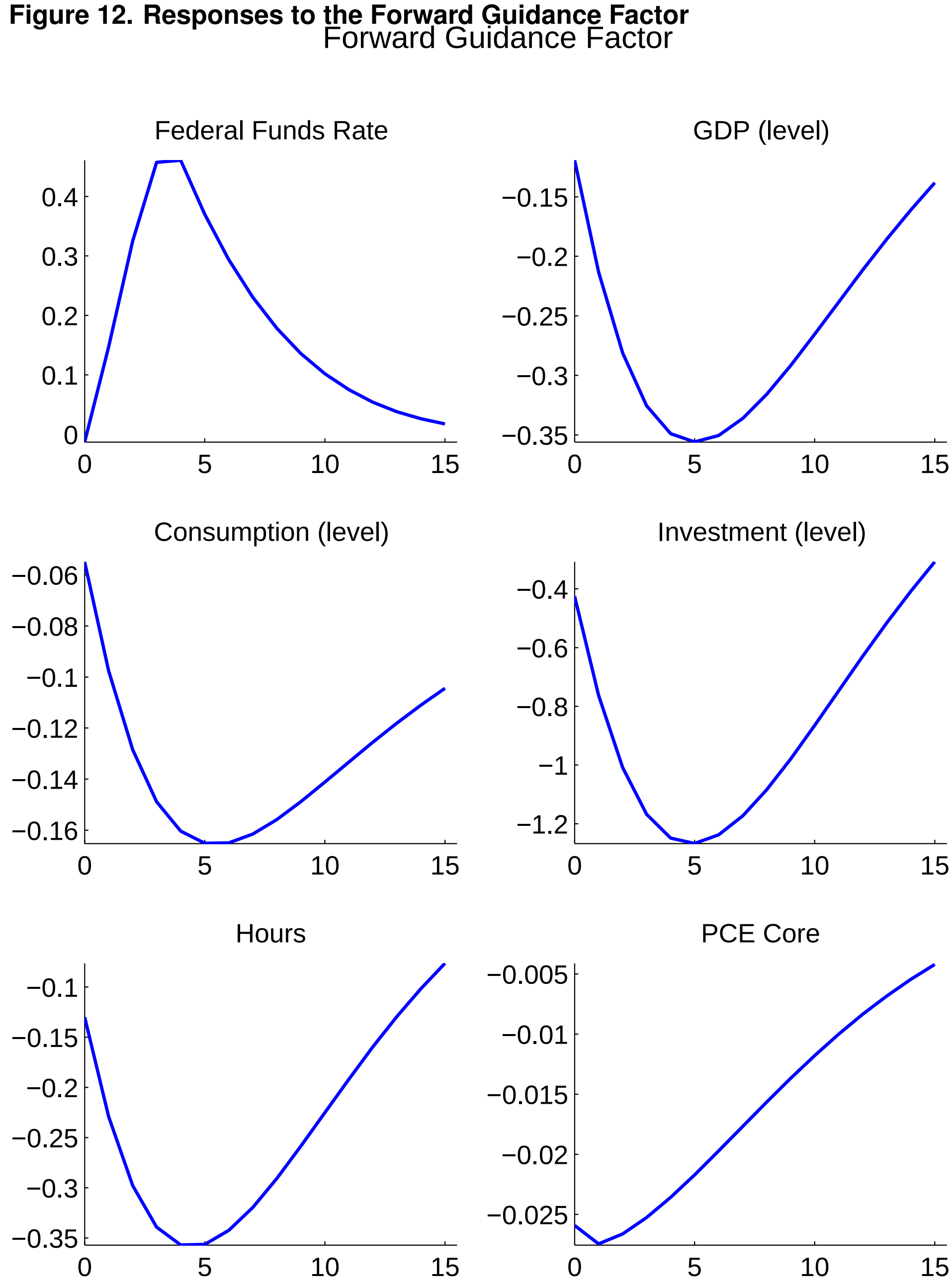
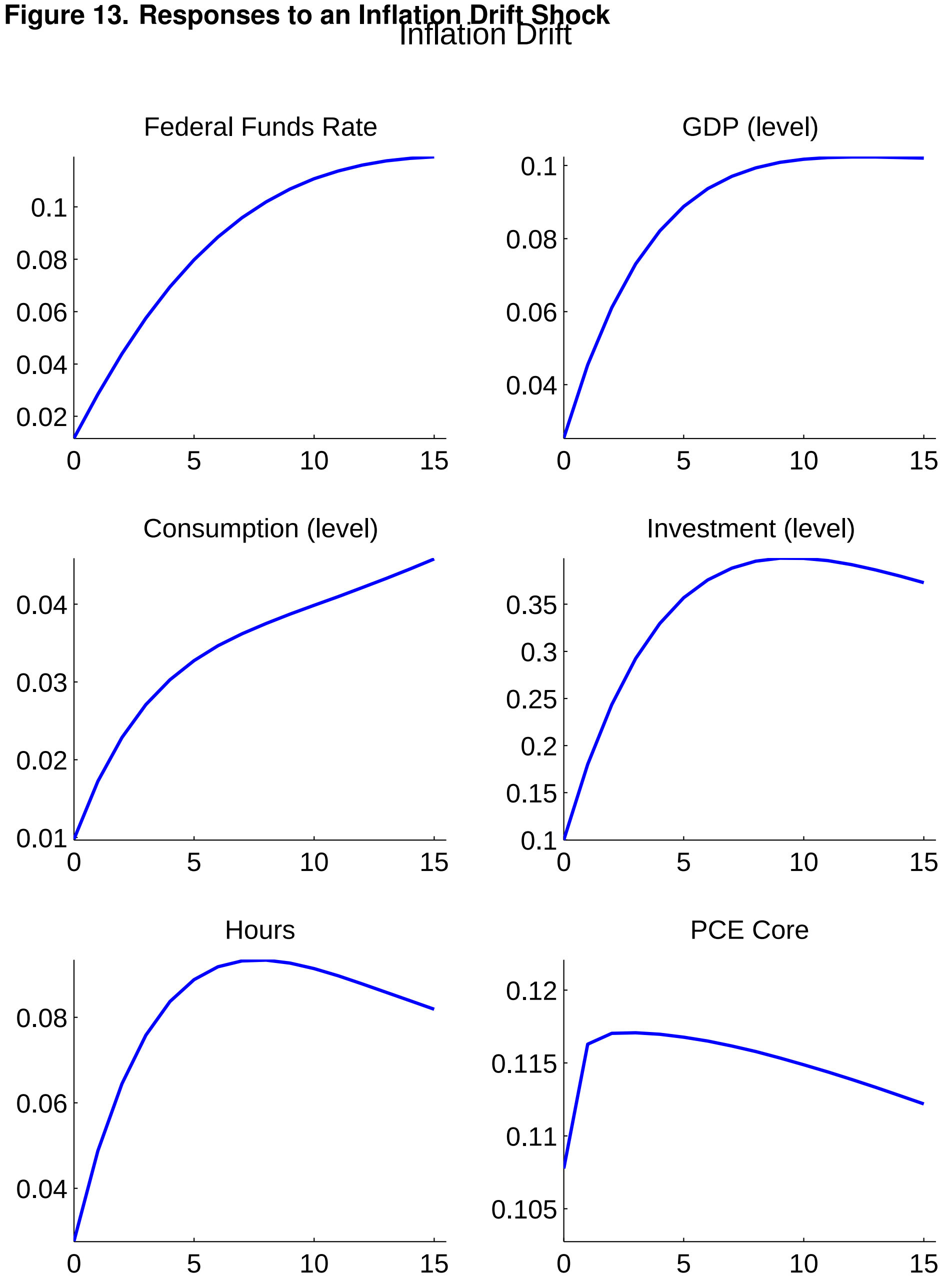


Figure 13. Responses to an Inflation Drift Shock



For concreteness, suppose that the forecasted object of interest is Q4-over-Q4 GDP growth for 2010. We position ourselves in 2009:Q4 and calculate

$$\begin{aligned}
\hat{\zeta}^{\text{2009:Q4}}_{\text{2010:Q1}} &\equiv F(\hat{\theta})\hat{\zeta}_{\text{2009:Q4}} \\
\hat{\zeta}^{\text{2009:Q4}}_{\text{2010:Q2}} &\equiv F(\hat{\theta})\hat{\zeta}^{\text{2009:Q4}}_{\text{2010:Q1}} \\
&= F^2(\hat{\theta})\hat{\zeta}_{\text{2009:Q4}} \\
&\vdots \\
\hat{\zeta}^{\text{2009:Q4}}_{\text{2010:Q4}} &\equiv F(\hat{\theta})\hat{\zeta}^{\text{2009:Q4}}_{\text{2010:Q3}}
\end{aligned}$$

These are the "expectations" of the model's states in each quarter of 2010 conditional on the state at the end of 2009 equalling its estimated value.

With these "state forecasts" in hand, we can construct corresponding forecast errors by comparing them with their "realized values" from the Kalman smoother. For the period t state forecasted in 2009:Q4, we denote these with

$$\hat{\eta}^{\text{2009:Q4}}_t = \hat{\zeta}_t - \hat{\zeta}^{\text{2009:Q4}}_t.$$

These forecast errors are related to the structural shocks by

$$\hat{\eta}^{\text{2009:Q4}}_t = \sum_{j=1}^{t-\text{2009:Q4}} F^{j-1}(\hat{\theta})\hat{\varepsilon}_{\text{2009:Q4}+j}.$$

The shock decomposition is based on four alternative forecasts, $\hat{\zeta}(\iota)^{\text{2009:Q4}}_t$ for $t = \text{2010:Q1}, \ldots, \text{2010:Q4}$ and $\iota \in \{\mathcal{D}, \mathcal{S}, \mathcal{M}, \mathcal{R}\}$. Here, ι indexes one of the four groups of structural shocks. For these, let $\hat{\varepsilon}(\iota)_t$ denote a version of $\hat{\varepsilon}_t$ with all shocks except those in group ι set to zero. With these, we construct

$$\begin{aligned}
\hat{\zeta}(\iota)^{\text{2009:Q4}}_{\text{2010:Q1}} &\equiv F(\hat{\theta})\hat{\zeta}_{\text{2009:Q4}} + \hat{\varepsilon}(\iota)_{\text{2010:Q1}}, \\
&\vdots \\
\hat{\zeta}^{\text{2009:Q4}}_{\text{2010:Q4}} &\equiv F(\hat{\theta})\hat{\zeta}^{\text{2009:Q4}}_{\text{2010:Q3}} + \hat{\varepsilon}(\iota)_{\text{2010:Q4}},
\end{aligned}$$

and

$$\hat{\eta}(\iota)_t^{2009:Q4} \equiv \hat{\zeta}_t - \hat{\zeta}(\iota)_t^{2009:Q4}.$$

By construction,

$$\hat{\eta}_t^{2009:Q4} = \sum_{\iota \in \{\mathcal{D},\mathcal{S},\mathcal{M},\mathcal{R}\}} \hat{\eta}(\iota)_t^{2009:Q4}.$$

That is, each forecast error can be written as the sum of contributions from each of the shock groups. Using the observation equations, we transform these into components of the forecast error for observable variables.

With this completed, we can then move the forecast date forward to 2010:Q1. The decomposition for that date proceeds similarly, except that we treat growth in 2010:Q1 as data.

Bibliography

Barro, R. J. and R. G. King (1984). Time-separable preferences and intertemporal-substitution models of business cycles. *The Quarterly Journal of Economics 99*(4), pp. 817–839.

Bernanke, B. S., M. Gertler, and S. Gilchrist (1999). The financial accelerator in a quantitative business cycle framework. *Handbook of Macroeconomics*.

Boivin, J. and M. Giannoni (2006). DSGE models in a data-rich environment. Working Paper 12772, National Bureau of Economic Research.

Campbell, J., J. Fisher, and A. Justiniano (2012). FOMC forward guidance and the business cycle. Working Paper, Federal Reserve Bank of Chicago.

Curdia, V., A. Ferrero, G. C. Ng, and A. Tambalotti (2011). Evaluating interest rate rules in an estimated DSGE model. Working Paper 510, Federal Reserve Bank of New York.

Greenwood, J., Z. Hercowitz, and G. W. Huffman (1988). Investment, capacity utilization, and the real business cycle. *The American Economic Review 78*(3), pp. 402–417.

Justiniano, A., G. E. Primiceri, and A. Tambalotti (2011). Investment shocks and the relative price of investment. *Review of Economic Dynamics 14*(1), 101–121.