Are Prices Sticky or just Backward-Looking?
*(Preliminary)*

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Abstract  
This paper contributes to the address of two questions emphasized in the recent literature on models of the role of monetary policy in the economy. The first concerns the consistency of the New Keynesian sticky price model with the high degree of persistence in inflation. The second concerns the possibility that perceived differences in the behavioral relationship between inflation, interest rates, and real variables across time may be attributable to a switch from “passive” to “active” monetary policy after 1979. I first show how passive policy can have very different implications with respect to the persistence of inflation. I then estimate parameters of a fairly standard model in this class; and I find little evidence against the hypothesis that monetary policy has been passive over the entire period 1959-2001. Moreover, my findings indicate little role for price stickiness. I suggest an interpretation of the real volatility of the early 1980s somewhat different from the mainstream view.

1 Introduction  
This paper contributes to the address of two questions emphasized in the recent literature on models of the role of monetary policy in the economy. The first concerns the consistency of the New Keynesian (“NK” hereafter) sticky price model with the high degree of persistence apparent in inflation data. The second concerns the possibility that perceived differences in the behavioral relationship between inflation,
interest rates, and real variables across time may be attributable to a switch from “passive” to “active” monetary policy after 1979.

With respect to the implications of equilibria under passive monetary policy, characterized by low reactivity to inflation on the part of the monetary authority in its setting of the interest rate, the literature has focussed on the possibility of extra-fundamental volatility in equilibrium. Following Clarida et al. (1999), the standard argument is that passive monetary policy practiced before the 1980s allowed such effects, and that this may have been an important contributor to volatility in the real economy. Furthermore, the argument goes, policy has been active since the third quarter of 1979, and this has induced a more controlled economy responsive only to fundamental shocks.

In another strand of this literature, skeptics following Fuhrer and Moore (1995) have observed that price stickiness is not synonymous with inflation stickiness, and, in fact, the persistence in inflation data may be hard to square with the canonical model.

I offer an some perspective on the mechanics underlying this difficulty with the basic model in Section 3 of the paper. There it is shown how equilibria under active policy exhibit a basic negative functional relationship between current and lagged inflation unless firms’ cost of adjustment of prices is substantial. Moreover, I suggest a link between the two questions described above by showing how passive monetary policy admits equilibria in which inflation is backward-looking, and shows fundamental persistence and inertia. These properties are exhibited by backward-looking equilibria independent of the level of price stickiness. In this respect, such equilibria are qualitatively consistent with the data, and, in fact, remove much of the empirical rationale for price stickiness. Of course, the mainstream view is that policy has precluded this possibility since the third quarter of 1979.

Following Lubik and Schorfheide (2004, “LS” hereafter), I estimate the parameters of a relatively standard NK model allowing for parameterizations admitting indeterminacy in equilibrium – i.e., passive monetary policy. At odds with the findings of LS and other work in the literature, I find little evidence contrary to the hypothesis that monetary policy has been passive for the entire period 1959-2001. For every subsample that I examine, the data support a backward-looking equilibrium explanation. Moreover, the hypothesis that prices are fully flexible – that prices are not sticky – is not rejected by the full dataset under my preferred (“benchmark”) parameterization. The equilibrium that the data prefer induces the observed inertia

\[1\] In what follows, I use the term “inertia” to refer to the lack of response to contemporaneous shocks. “Persistence” may refer in different contexts to statistical autocorrelation, or to functional dependence on own-lags.
and persistence in inflation internally without significant frictions in price adjustment.

The rest of this paper is structured as follows. The next section describes the version of the NK model that I will work with and the precise nature of the policy rules that I consider. The third section attempts to provide some intuition for the behavior of inflation by inspecting the mechanism. The fourth section present the results and interprets them; and the final section summarizes the main points and concludes.

2 Model

The structure of the model and my empirical implementation follow the spirit of the “small structural model” approach of Rotemberg and Woodford (1997), Ireland (1997, 2000, 2003b), McCallum and Nelson (1999), and Lubik and Schorfheide (2004). Most of the elements of the model are familiar, and I will be brief in my description.

The economy consists of a representative household, a representative final goods producer, a continuum of producers of differentiated intermediate goods, and a monetary authority. The time horizon is infinite.

The household acts to maximize expected lifetime utility given by

$$E_0 \sum_{t=0}^{\infty} \beta^t a_t \left[ \ln c_t + \ln \left( \frac{m_t}{P_t} \right) - \gamma h_t \right],$$

where $c_t$, $m_t$, $P_t$, $h_t$, and $a_t$ are stochastic processes representing consumption, nominal money balances, the price level, labor supply, and an exogenous preference shock, respectively. Preference shocks are assumed to follow the autoregressive process

$$\ln a_t = \rho_a \ln a_{t-1} + \varepsilon_t^a,$$

where $|\rho_a| < 1$ and $\varepsilon_t^a$ is a zero-mean white noise process. The household chooses consumption, money, and labor supply in each period subject to the budget constraints

$$P_t c_t + m_t + b_t = P_t w_t h_t + m_{t-1} + R_{t} b_{t-1} + d_t,$$

where $b_t$ is nominal bonds held at the end of period $t$, $w_t$ is the real wage, and $d_t$ is profit distributions from ownership of the firms in the economy.

The representative final goods producer uses a continuum of intermediate inputs
\( \hat{y}_t(i), i \in [0, 1] \) to produce output \( y_t \) according to the technology

\[
y_t = \left\{ \int_0^1 \left[ \hat{y}_t(i) \right]^{\theta_t-1} \right\}^{\theta_t/(\theta_t-1)},
\]

where \( \theta_t \) is an exogenous stationary stochastic process obeying

\[
\ln (\theta_t - 1) = \ln (\theta - 1) + \rho_\theta \ln (\theta_{t-1} - 1) + \varepsilon^\theta_t,
\]

|\( \rho_\theta | < 1, and \( \varepsilon^\theta_t \) is a zero-mean white noise process.\(^2\)

Taking the output price \( P_t \) and the continuum of input prices \( \hat{P}_t(i) \) as given, profit maximization by this firm is easily seen to induce input demand functions of the form

\[
\hat{y}_t(i) = \left( \frac{\hat{P}_t(i)}{P_t} \right)^{-\theta_t} y_t
\]

for any choice of output \( y_t \). Thus, \(-\theta_t\) is the (time-varying) price elasticity of demand for an intermediate input. Given constant returns to scale in production, standard arguments suggest that the firm must earn zero profit in any equilibrium, which implies that the price of final goods must satisfy

\[
P_t = \left\{ \int_0^1 \left[ \hat{P}_t(i) \right]^{1-\theta_t} \right\}^{1/(1-\theta_t)}.
\]

Intermediate goods producer \( i \) hires labor \( \hat{h}_t(i) \) and produces intermediate \( i \) according to the technology

\[
\hat{y}_t(i) = Z_t \hat{h}_t(i),
\]

where \( Z_t \) is an exogenous stochastic productivity shock following random walk with drift:

\[
\ln Z_t = \ln g + \ln Z_{t-1} + \varepsilon^Z_t,
\]

and \( \varepsilon^Z_t \) is zero-mean white noise. These firms also incur (real) costs of price adjustment (in units of final goods) equal to

\[
\frac{\phi}{2} \left[ \frac{\hat{P}_t(i)}{\Pi \hat{P}_{t-1}(i)} - 1 \right]^2 y_t,
\]

\(^2\)This particular form for the elasticity shock \( \theta_t \) has been chosen to ensure that \( \theta_t > 1 \) for all \( t \), which is necessary to ensure the existence of a well-behaved equilibrium.
where $\phi \geq 0$ and $\Pi > 0$ are parameters.

In a symmetric equilibrium of the economy, all intermediate goods producers make the same optimal choices in each period, so that $\bar{P}_t (i) = P_t, \hat{h}_t (i) = \int_0^1 \hat{h}_t (i) = h_t$, and $\hat{d}_t (i) = \int_0^1 \hat{d}_t (i) = d_t$. It follows from (6) that $\hat{y}_t (i) = y_t$, and the final goods market clearing condition can be seen to be

$$c_t = \left[ 1 - \frac{\phi}{2} \left( \frac{\Pi_t}{\Pi} - 1 \right) \right]^2 y_t,$$

where $\Pi_t \equiv P_t / P_{t-1}$. Appendix A develops the firm’s problem in greater detail; and shows how the market clearing condition, and the first-order conditions from the problems of the household and a representative intermediate goods producer may be combined and linearized to yield the approximating equations

$$E_t \hat{h}_{t+1} + E_t \hat{\Pi}_{t+1} - E_t \hat{a}_{t+1} = \hat{h}_t + \hat{R}_t - \hat{a}_t$$

$$\left( \omega g / R \right) E_t \hat{\Pi}_{t+1} = \omega \hat{\Pi}_t - \hat{h}_t + \hat{\theta}_t,$$

where

$$\omega \equiv \frac{\phi}{\theta - 1},$$

$$\hat{\theta}_t \equiv \frac{\theta_t - \theta}{\theta (\theta - 1)},$$

and other variables with carets should be interpreted as log-deviations from a non-stochastic steady-state. The literature interprets (11) as an “expectational IS” curve, and (12) as a “New Keynesian Phillips curve”. Following Ireland (2004), I refer to $\theta_t$ as a “markup” shock.3

To close the model, it is assumed that the monetary authority sets the nominal interest rate in each period to follow a feedback rule described by

$$\hat{R}_t = \rho_R \hat{R}_{t-1} + (1 - \rho_R) R^*_t + v_t,$$

where $R^*_t$ is a target for the nominal interest rate, $\rho_R \in [0, 1]$ is a parameter, and $v_t$ is an exogenous stationary stochastic process affecting the conduct of monetary policy. I assume that the policy shock follows

$$\ln v_t = \rho_v \ln v_{t-1} + \xi^v_t,$$
where $\varepsilon_t^v$ is a white noise process. I consider two alternative specifications for the target rate. The first type of policy rule I consider has

$$R_t^* = \nu_\pi \hat{\Pi}_{t-1} + \nu_h \hat{h}_{t-1}, \quad (15)$$

where $\nu_\pi$, and $\nu_h$ are parameters; following Bullard and Mitra (2002), I will refer to such specifications as “lagged data” policy rules. The second alternative, which Bullard and Mitra (2002) call a “contemporaneous expectations” policy rule, has the form

$$R_t^* = \nu_\pi E_{t-1} \hat{\Pi}_t + \nu_h E_{t-1} \hat{h}_t. \quad (16)$$

The parameter $\nu_\pi$ in each specification plays a special role in the model and in the literature. As I discuss in the next section, it often obtains that the determinacy of a stable equilibrium hinges upon its value. Looking forward, it will be useful to refer to rules with $\nu_\pi > 1$ as “active”, and to those with $0 \leq \nu_\pi < 1$ as “passive”.

### 3 Properties of Equilibria under Active and Passive Policy

In this section, I will attempt to build some intuition for the results to follow. In particular, I discuss qualitative differences between the behaviors of the model described in the previous section under active and passive policy rules.

First consider the model under lagged data policy rules; and, for simplicity, begin with the analytically simpler case of fully flexible prices. With $\phi = 0$, (12) implies that $\hat{h}_t = \hat{\theta}_t$; and (11), (13), and (15) may be collapsed into

$$E_t \hat{\Pi}_{t+1} = \hat{R}_t - (1 - \rho_u) a_t + (1 - \rho_h) \theta_t \quad (17)$$

and

$$\hat{R}_t = \rho R \hat{R}_{t-1} + (1 - \rho_R) \nu_\pi \hat{\Pi}_{t-1} + (1 - \rho_R) \nu_h \hat{h}_{t-1} + \hat{v}_t. \quad (18)$$

These two equations can be combined to yield a single equation characterizing the behavior of inflation in equilibrium,

$$E_t \hat{\Pi}_{t+1} - \rho R E_{t-1} \hat{\Pi}_t - (1 - \rho_R) \nu_\pi \hat{\Pi}_{t-1} = x_t, \quad (19)$$

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4See Bullard and Mitra (2002), e.g.
where
\[
x_t = -(1 - \rho_a) \hat{a}_t + \rho_R (1 - \rho_a) \hat{a}_{t-1} + (1 - \rho_\theta) \hat{\theta}_t \\
+ [-\rho_R (1 - \rho_\theta) + (1 - \rho_R) \nu_h] \hat{\theta}_{t-1} + \hat{v}_t.
\]

It is shown in Appendix B that (19) has no stable solution with \( \hat{\Pi}_{t-1} \) predetermined at \( t \) for generic shocks \( x_t \) unless
\[
\nu_\pi < \bar{\nu}_\pi \equiv \frac{1 + \rho_R}{1 - \rho_R};
\]
and that there is a unique stable solution in this class whenever \( \nu_\pi \in (1, \bar{\nu}_\pi) \). With this restriction, the “forward-looking” solution is given by
\[
\hat{\Pi}_t = \lambda_1 \hat{\Pi}_{t-1} + \frac{1}{\lambda_1 \lambda_2} \sum_{j=0}^\infty \lambda_2^{-j} E_{t+1} x_{t+j} - \frac{1}{\lambda_1 \lambda_2} \sum_{j=0}^\infty \lambda_2^{-j} E_{t-1} x_{t+j} + \frac{1}{\lambda_1} x_t,
\]
where
\[
\lambda_1 \equiv \frac{\rho_R}{2} - \sqrt{\left(\frac{\rho_R}{2}\right)^2 + (1 - \rho_R) \nu_\pi}
\]
and
\[
\lambda_2 \equiv \frac{\rho_R}{2} + \sqrt{\left(\frac{\rho_R}{2}\right)^2 + (1 - \rho_R) \nu_\pi}.
\]

Considering the effect of exogenous shocks, the dynamic behavior of inflation implied by (20) may be quite complex. Yet some basic features of this solution may be gleaned. These are discussed next.

First, note that the autoregressive coefficient (i.e., \( \lambda_1 \)) is negative, indicating a basic tendency to oscillatory dynamics in response to an impulse in \( x_t \). Consider, for example, the effect of a positive innovation in monetary policy when such shocks are i.i.d. That is, let \( v_0 = \varepsilon_0^\nu \) and \( v_t = 0 \) for \( t > 0 \). In this case, inflation will fall immediately by the amount \( |\lambda_1^{-1} \varepsilon_0^\nu| \); and the forecasts of inflation \( \tau \) periods in the future will rise by \( \lambda_1^{-1} \varepsilon_0^\nu \). This response is precisely what is necessary under the given policy rule to leave contemporaneous and future (expected) real interest rates, say \( \hat{\rho}_t \equiv \hat{R}_t - E_t \Pi_{t+1} \), unchanged for \( t \geq 0 \).

Satisfying intuition, it may be seen (e.g., by numerical simulation) that these

\[5\) Note that, under flexible prices (11) and (12) imply that
\[
\hat{\rho}_t = (1 - \rho_a) \hat{a}_t - (1 - \rho_\theta) \hat{\theta}_t,
\]
oscillations are apparent in response to (i.i.d.) policy shocks when the price stickiness parameter $\phi$ is close to zero, and that they disappear for larger values. The important implication is that internal persistence in inflation is induced only if there is substantial stickiness in prices; alternatively, only the nature of the exogenous shocks saves the implied inflation process from showing negative autocorrelation.

Dashed lines in Figure 1 show how changes in various parameters affect the inflation autocorrelation functions implied by the model under active (lagged data) policy rules. The solid lines in each panel of the figure show the analogous object obtained from a three variable VAR. In the experiments, the inflation weight $\nu_\pi$ is set equal to 1.2571; except as noted, other parameters are held equal to the values shown in column (1) of Table 1 in the next section.\(^6\) Panel (a) shows the effect of varying the quantity $\omega \equiv \phi / (\theta - 1)$ from 0 to 100 (bottom to top), illustrating the effect of changing of the price adjustment cost parameter; and panels (b)-(d) show the effect of raising $\rho_a$, $\rho_b$, and $\rho_v$ (respectively) from the values shown in column (1) of Table 1. Apparently, substantial price stickiness is necessary if such a specification is to match the persistence of inflation in the data.

Now consider a “backward-looking” solution induced by parameterizations with $\nu_\pi \in (0, 1)$.\(^7\) In this case, there exist a multiplicity of solutions to (19) of the form

$$\Pi_t = \rho_R \Pi_{t-1} + (1 - \rho_R) \nu_\pi \Pi_{t-2} + x_{t-1} + \xi_t,$$

where $\xi_t$ (a “sunspot”) satisfies $E_t \xi_t = 0$. Note that the autoregressive parameters of the backward-looking solution are inherited from the policy rule. Under our assumptions, these coefficients are non-negative, so that the dynamics internal to the equilibrium will tend to induce positive autocorrelation in inflation.

Under passive policy, extra-fundamental effects may obtain from a sunspot, or from a non-fundamental effect of fundamental shocks.\(^8\) However, in the absence of such effects, the fundamental shocks of the environment do not affect inflation contemporaneously. Thus, both persistence and inertia may be intrinsic to these backward-looking solutions.

As noted by King (2000), the response to an impulse in the driving process is positive. Thus, the initial response of inflation to preference shocks will be negative, and that to policy and markup shocks will be positive.

\(6\) The value 1.2571 for $\nu_\pi$ is that estimated by Ireland (2001) for the analogous parameter in a closely related model.

\(7\) Here, inflation is “backward-looking” precisely in the sense of Klein (2000); its one step ahead prediction error $\Pi_{t+1} - E_t \Pi_{t+1}$ is an exogenous martingale difference sequence.

\(8\) Kerr and King (1996) offer some examples, and some illuminating discussion.
Figure 1: The dashed lines show inflation autocorrelation functions from forward-looking solutions under various assumptions about the price adjustment cost parameter and the persistence of the model’s shocks. In (a), the quantity $\omega \equiv \phi/(\theta - 1)$ takes on the values (bottom to top) 0, 1, 10, and 100. In (b), $\rho_\alpha$ is set to (bottom to top) 0.9273, 0.99, and 0.995. In (c), $\rho_\theta$ is set to (bottom to top) 0.9718, 0.99, and 0.995. In (d), $\rho_v$ is set to (bottom to top) 0.2118, 0.9, and 0.95. In each case $\nu_\epsilon$ is set equal to 1.2571, and other parameters are set equal to those in column (1) of Table 15 below. The solid lines show the autocorrelation of inflation at various lags obtained from a three variable VAR.
Sims (1992) and other researchers have documented the tendency of the price level to rise following an innovation to the short term interest rate. Received as a “price puzzle”, this observation is entirely consistent with backward-looking equilibria, even in the absence of price adjustment costs.\footnote{See Walsh (2003) for a useful discussion of the literature on the “price puzzle”.}

Turning now to contemporaneous expectations policy rules (16), the centrality of price adjustment costs in the model under active monetary policy is even more brutal; there is no equilibrium for rules of this sort under fully flexible prices.\footnote{This finding is related to the results of Bernanke and Woodford (1997).} To see this most simply, note that the derivation analogous to the one that gave us (19) now delivers

\[ E_t \Pi_{t+1} - [\rho_R + (1 - \rho_R) \nu_\pi] E_{t-1} \Pi_t = x_t. \]  

(21)

For the case that \( \nu_\pi > 1 \), we have

\[ \chi \equiv \rho_R + (1 - \rho_R) \nu_\pi > 1, \]

and (21) implies that

\[ E_{t-1} \Pi_t = \sum_{j=0}^{\infty} \chi^{-j-1} x_{t+j}. \]  

(22)

For non-degenerate shock processes, (22) obviously violates the necessity that \( E_{t-1} \Pi_t \) is a function of variables in the time \( t - 1 \) information set.

While the analytical solution of the model with positive price adjustment costs is too complex to offer useful intuition, Figure 2 displays the salient features analogous to those shown in the previous figure. Here, except for the inflation weight, the parameters unaffected by each experiment are held at the benchmark values described in Table 3. Panel (a) shows (bottom to top) the effect of varying \( \omega \) from 0.1660 to 100; and panels (b)-(d) show the effect of raising \( \rho_\alpha, \rho_\theta, \) and \( \rho_\nu \) (respectively) from the values shown in column (1) of Table 3.\footnote{The lowest setting for \( \omega \), which is positive as necessitated by existence of an equilibrium, is the point estimate obtained from estimation of the model allowing for a backward-looking solution.} Once again, the important role of price stickiness in inducing realistic inflation persistence is apparent.

In contrast, passive monetary policy admits passive monetary policy admits a backward-looking solution for the model with fully flexible prices of the simple form

\[ \Pi_t = [\rho_R + (1 - \rho_R) \nu_\pi] \Pi_{t-1} + x_{t-1} + \xi_t. \]

Qualitatively, this solution shows many of the same properties as the backward-looking solution.\footnote{Note that for shock processes that are not degenerate, (22) obviously violates the necessity that \( E_{t-1} \Pi_t \) is a function of variables in the time \( t - 1 \) information set.}
Figure 2: The inflation autocorrelation functions from forward-looking solutions under various, contemporaneous expectations policy rule. In (a), $\omega$ takes on the values (bottom to top) 0.1660, 1, 10, and 100. In (b), $\rho_\alpha$ is set to (bottom to top) 0.9060, 0.95, and 0.99. In (c), $\rho_\theta$ is set to (bottom to top) 0.9720, 0.99, and 0.995. In (d), $\rho_v$ is set to (bottom to top) 0.2007, 0.9, and 0.95. Other parameters are set equal to those estimated for the full sample under the contemporaneous expectations policy rule as discussed below. The solid lines show the autocorrelation of inflation at various lags obtained from a three variable VAR.
looking solution discussed above for the case of the lagged data policy rule. In particular, positive autocorrelation and inertia in inflation are basic to the solution.

It has been acknowledged that I have focused on a particular form for the equilibrium solution among many possible alternatives for versions of the model passive monetary policies. I have tried to motivate equilibria with backward-looking inflation as deserving of some special interest and focus on empirical grounds. One may reasonably argue that there is little hope that I will identify the “right” model, since I have arbitrarily precluded consideration of equilibria that are arbitrarily close to those I have allowed. The approach might tell us something about which models or model features are potentially “wrong”, however.

4 Estimation of the Model

4.1 Description of the Estimation Exercises

To provide formal evidence on the nature of the dynamics of inflation, employment, and interest rates, the parameters of the model are estimated by maximizing the likelihood of the data under the assumption of Gaussian shocks. This subsection describes some of the details, and the rest of this section describes the results.

The nature of this exercise has much in common with the work of Lubik and Schorfheide (2004, LS), though my approach is much more straightforward. First, and most obviously, they follow a Bayesian approach in which a central objective is to assess the posterior probability that the data follow a deterministic equilibrium (under active monetary policy). In contrast, I simply evaluate the parameterization that maximizes the likelihood function. Second, LS allow for very general forms of indeterminacy, where I search the parameter space imposing that inflation is backward-looking whenever the parameterization admits indeterminacy. In the previous section, I described the empirical merit of such solutions. At the price of generality, then, my findings offer ready interpretation. Third, LS explore policy rules utilizing contemporaneous data, rather than lagged data or lagged expectations of contemporaneous data.

Less importantly, the model I have described motivates the focus on employment, rather than output, fluctuations. Informal experiments lead me to believe that the results would not be substantially changed by considering a model according to which output fluctuations were more central.\footnote{Most formulations of the New Keynesian sticky price model are in this class. Such a version obtains, for example, if one assumes that the technology shock $Z_t$ follows a stationary AR(1) process, rather than a random walk.} My view is that employment fluctuations
are probably equally important in the view of policymakers, and that the business cycle may be more easily extracted from employment data.\footnote{My perception is that detrending of output data leaves a time-series that displays too-low frequency cycles. As an alternative, LS apply the Hodrick-Prescott filter to their output series prior to estimation of their model. Following that approach, however, it seems conceptually inappropriate to subsequently apply the Kalman filter; that is, application of the HP filter may invalidate that approach to factorization of the likelihood function.}

Responding to the tide of the literature, and in order to investigate the efficacy and nature of policy regime change, I will estimate my model on a full sample of data spanning the 1979 monetary policy reforms, a subsample ending in 1979:III, and a subsample beginning in 1979:IV. Following Clarida et al (2000) and LS, I also estimate the model on a post-1982 subsample to investigate the possibility that the interim period shows special features attributable to the need of agents to coordinate on a new equilibrium following a change of the policy rule.

Sims and Zha (2006) have argued against the practice of imposing discontinuous policy change at a point in time fixed exogenously, or splitting a data sample based on the perception of policy change and its effective importance. Anticipating the results, I view my findings as supportive of this view; and my assessment of the implications of the model in Subsections 4.6 and 4.7 maintains implicitly that features endogenous to the model have generated the perception.

4.2 Data

I use quarterly data on the GDP implicit price deflator, and quarterly averages of monthly data for the three month T-Bill rate and the employment-population ratio for the third quarter of 1959 to the third quarter of 2001. These data were obtained from the Federal Reserve Economic Databank (FRED) at the Federal Reserve Bank of St. Louis. The detrended logarithm of the employment-population ratio is my proxy for $\hat{h}_t$; $\Pi_t$ is the demeaned difference of logarithms of the GDP deflator; and $\hat{R}_t$ is one-fourth of the logarithm of one plus the T-Bill rate in decimal representation.

4.3 Estimates of Model under Lagged Data Policy Rule

This subsection discusses briefly the results from estimation of the model under a lagged data policy rule for the full data sample, and for the three subsamples, as discussed above. More attention will be devoted to discussion of the estimates for the model under the contemporaneous expectations rule in the following subsection, for reasons that I will describe.
Table 1 summarizes the results for this specification. The point estimates for the full sample and for each of the subsamples induce indeterminacy in the selection of a stable equilibrium, which is resolved by imposing that inflation is backward-looking, as described above.

Point estimates of the value of $\omega$ in each subsample are low in comparison to others in the literature, suggesting that the economy devotes only a small fraction of resources to adjustment of prices. In fact, data from two of the subsamples fail to reject the hypothesis of fully flexible prices at the 95% level; the results from likelihood ratio tests are summarized by values in the row labeled “$\omega = 0$, p-value”.\(^\text{14}\) It is apparent from the Table 1 that standard $t$-tests corroborate this finding.

Likelihood ratio test results summarized in the row labeled “$\sigma_\xi = 0$, p-value” show that estimates for all but one of the subsamples reject the hypothesis that the variance of extra-fundamental shocks is zero.\(^\text{15}\) Thus, sunspots may be an important component in the explanation of the dynamic behavior of interest. This notion is discussed in more detail in the context of the alternative policy rule in following sections.

Point estimates of the parameters governing the model’s fundamental shocks appear to be consistent with estimates obtained elsewhere, though autoregressive coefficients may be thought to show somewhat less persistence than estimates obtained from New Keynesian models elsewhere.\(^\text{16}\)

Comparison of the estimates of the policy parameters (i.e., $\nu_\pi$, $\nu_h$, $\rho_R$, $\rho_v$, and $\sigma_v$) across subsamples reveals a great deal of inconsistency. Especially troubling is the (imprecise) negative estimate of the inflation weight for the post-1982 subsample. To shed some light on the appropriate interpretation of this finding, Table 2 presents maximum likelihood estimates of the policy equation in isolation.\(^\text{17}\) Commonalities are apparent; most of the parameters are close across the two estimation procedures. For example, despite reasonable precision, standard $t$-tests would not reject equality in any analogous pairing. Even the negativity of the inflation weighting in the case of the post-1982 subsample is repeated. This suggests that inconsistencies may be isolated to the specification of the policy rule. In conjunction with the results de-

\(^{14}\)Under the null hypothesis that $\omega = 0$, two times the negative change of the maximized log-likelihood after imposition of the constraint is a draw from the $\chi^2(1)$ distribution.

\(^{15}\)The null hypothesis again induces a comparison of twice the change in the likelihood to the $\chi^2(1)$ distribution.

\(^{16}\)Compare the results of Ireland (2003, 2004), for example.

\(^{17}\)Under the lagged data policy rule, the policy targets are predetermined with respect to the innovation in the policy rule. This feature permits separate estimation of this equation. Separate estimation of the contemporaneous expectations policy rule, which is not undertaken in this paper, would be less straightforward.
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Table 1: Estimates of the model under the lagged data policy rule. Asymptotic standard errors (in parentheses) are obtained as the square root of diagonal elements of the inverse Hessian of the log-likelihood function.
Table 2: Single equation estimates of the lagged data policy rule. Asymptotic standard errors (in parentheses) are obtained as the square root of diagonal elements of the inverse Hessian of the log-likelihood function.

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<td>(0.23)</td>
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scribed next, I conclude that the lagged data policy rule appears to be misspecified as a structural equation.

4.4 Estimates of Model under the Contemporaneous Expectations Policy Rule

This subsection discusses the results from estimation of the model under a contemporaneous expectations policy rule. This version of the model, and particularly the parameterization obtained from the full sample point estimates, will be adopted as my “benchmark” in numerical experiments in subsequent subsections.

Table 3 summarizes the results. As for the lagged data policy rule, the point estimates for the full sample and for each of the subsamples imply indeterminacy of the equilibrium, which is resolved by imposing that inflation is backward-looking.

Point estimates of the value of \( \omega \) are once again small in each subsample, and the null hypothesis of fully flexible prices is rejected at the 95% level by the likelihood ratio test (or, indeed, standard \( t \)-tests) only by the post-1979 subsample.

Estimates for the full sample and two of the three subsamples suggest a significant role for sunspot shocks. The role of sunspots will be illuminated in more detail in discussion of a variance decomposition below, and in the presentation of unconditional estimates of the model’s shocks.

In agreement with the results described in the previous subsection, estimates of the parameters of fundamental shocks are broadly consistent with estimates obtained
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<tr>
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<td>(0.0001)</td>
<td>(0.0002)</td>
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<td>0.0000</td>
<td>0.9605</td>
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Table 3: Estimates of the model under the contemporaneous expectations policy rule. Asymptotic standard errors (in parentheses) are obtained as the square root of diagonal elements of the inverse Hessian of the log-likelihood function.
elsewhere in the literature. As before, my estimates show somewhat less persistence than is typical for estimates obtained from New Keynesian models; and the estimate of $\rho_a$ from the post-1979 estimate is somewhat out of line with those in the other columns. Overall, however, this evidence is consistent with the contention that too-high estimates of these parameters may be induced by restricting to the determinacy region of the parameter space.

Turning now to discussion of the policy parameters, first note the stark differences across the specifications of different policy rules. For example, the post-1982 subsample delivers a precise point estimate of 0.9148 for the inflation weight under the contemporaneous expectations policy, verses (an imprecise) −0.5795 under the lagged data rule. Note also that the maximized log-likelihood values are quite close for each subsample. These results constitute additional evidence that the lagged data rule is misspecified as a structural equation, though it may do reasonably well as a reduced form representation.

The results from a battery of likelihood ratio tests aimed at assessing the stability of contemporaneous expectations policy parameter estimates across subsamples can be summarized as follows. First, none of the subsamples rejects at the 95% level the null hypothesis that the inflation weight $\nu_\pi$ has the value estimated for the full sample; and none rejects the null hypothesis that both of the policy target weights, $\nu_\pi$ and $\nu_h$, are equal to the values estimated for the full sample. The null hypothesis that $\nu_\pi$, $\nu_h$, and the smoothing parameter $\rho_R$ are equal to the values estimated for the full sample is rejected at the 95% level only by the pre-1979 subsample. Finally, the null hypothesis that these three parameters as well as the persistence $\rho_v$ and the variance $\sigma_v$ of the policy shock (five parameters) are equal to the values estimated for the full sample is not rejected by the full sample or the post-1979 subsample.

In conclusion, my view is that the policy target weights for the contemporaneous expectations rule show a substantial degree of stability over time. This finding may be especially compelling, as the inflation target weight point estimate is reasonably precise in each subsample. The point estimates do appear to rise in later subsamples, and this finding may be thought consistent with a common perception that monetary policy has become more hawkish on inflation. Most importantly, however, I find no evidence counter to the hypothesis that monetary policy has been “passive” over the entire period.

---

18Likelihood ratio test statistics are draws from the $\chi^2(k)$ distribution, where $k$ is the number of parameters constrained by the null hypothesis.
4.5 Digression on Search algorithms, Local Maxima, and the Discontinuity of the Likelihood Function

Naturally, I have sought maxima of the likelihood function in the determinacy region of the parameter space. In every case, I have been unable to find local maxima robustly inside that region. The search proceeds delicately, as the likelihood function is not generally continuous at this boundary.

Golub and Van Loan (1989) describes a metric over a space of matrices that is useful for characterizing the proximity of a given parameterization of the model to the indeterminacy region. Precisely, the distance of a given matrix to the subspace of matrices of lower rank can be measured as the smallest non-zero value among the absolute values of eigenvalues of the matrix. Thus, for parameterizations in the determinacy region, the distance from the boundary can be measured by assessing this value with respect to an appropriate matrix derived in the course of solving the model (by Klein’s (2000) method, e.g.).

As a result of the discontinuity of the likelihood function, and the fact that the determinacy region is an open set in the parameter space, it frequently obtains that numerical search algorithm starting from a parameterization in the determinacy region terminates in the same region. In this case, the measured distance to the indeterminacy region is necessarily positive. In each attempt, however, I have found this distance to be small, indicating a pathology of the algorithm rather than a local maximum.

In short, I have been unable to find local maxima in the determinacy region for any of the subsamples considered using a variety of seed values. Moreover, the values of the log-likelihood function that do obtain at the termination of these procedures are typically hundreds of points below the true maxima.

4.6 Variance Decomposition and Model Dynamics

In this subsection, I present the results of a forecast error variance decomposition, and discuss impulse response functions and the vector autocorrelation function implied by the benchmark parameterization obtained from the full sample estimates under the contemporaneous expectations policy rule.

Figure 3 displays the contributions of each of the four types of shocks to the forecast error variance of each of the models variables at various horizons.

For employment, nearly all of the variance is attributed to markup shocks at every forecast horizon. This result stems entirely from the finding of price adjustment costs

19I confess that it is frustration at my accidental finding of this fact that spawned this research!
Figure 3: Variance decomposition based on estimates from the full sample under the lagged expectations policy rule. The contribution of IS, policy, and sunspot shocks is shown; that of markup shocks is left as the residual of the sum of the contributions to one.
Interest rate movements are dominated by policy shocks up to about eight quarters, where these account for 93.1% of the variance. In the long run, policy shocks contribute 67.7%, IS shocks 28.5%, and markup shocks 3.8%. Sunspots account for no more than 0.01% at any forecast horizon.

Sunspots appear to account for much of the uncertainty in inflation over short horizons, but much less at long horizons. By assumption, inflation does not respond contemporaneously to fundamental shocks in the equilibrium under passive monetary policy rules; thus sunspots account for all of the volatility at a horizon of one quarter. At four quarters, sunspots account for 15.2% of the forecast error variance, while the balance is attributable to IS shocks (49.5%) and policy shocks 39.1%. The dominant contributions to long run forecast error variance are those of IS (55.9%) and policy (37.4%), with 3.5% and 3.2% attributable to markup and sunspot shocks, respectively.

Figure 4 shows the responses of model variables to impulses in each type of shock. The leftmost column shows the change in the time path of the shock in response to a one-standard deviation impulse; columns 2-5 show the resulting change in the time path of employment, inflation, the nominal interest rate, and the (expected) real interest rate, respectively. It is notable that inflation shows a hump-shaped response to each variety of shock except the sunspot. Inflation responses peak for IS and policy shocks after two and three quarters, respectively; and the peak following a markup shock occurs after more than twenty quarters. Thus, these responses show a very high degree of persistence even to shocks that are only moderately persistent.

In every case, inflation and the nominal interest rate move in the same direction. Inflation shows a persistent positive response to a positive shock to policy. The nominal rate also responds positively to such shocks, so that the “price puzzle” phenomenon is exhibited. On net, positive policy shocks show a short-lived “contractionary” effect, raising the real interest rate for four quarters, and reducing employment for two quarters.

For the case of IS and markup shocks, the real interest rate moves in the direction opposite to inflation and nominal rates. The real rate rises after an IS shock, and falls after a markup shock.

Figure 5 shows the theoretical vector autocorrelation function induced by the benchmark parameterization (dashed line) along with that obtained from a three-variable vector autoregression (solid line). With respect to the inflation autocorrela-

\[ h_t = \hat{\theta}_t \] under fully flexible prices.

\[ \rho_t \equiv \hat{R}_t - E_t \hat{\Pi}_{t+1}. \]
Figure 4: Impulse responses to shocks according to the parameterization obtained from estimates of the lagged expectations policy specification using the full sample.
tion component, the degree of agreement is striking. These statistics reflect a central result of this paper that the empirical persistence in inflation is readily obtained in a model in which inflation is allowed to be endogenously backward-looking.

The degree to which the VAC functions agree in other dimensions may be debated. The employment data seem to exhibit less persistence in the data than in the model. It might be suspected, however, that allowing persistence in the shocks to technology growth would permit a more realistic fit in this dimension, since such persistence in the data is left according to the model to be explained by other shocks.

It is apparent that the (negative) correlations of employment with lagged interest rates exhibit properties similar to the analogous correlations with employment replaced by output; following King and Watson (1996), this phenomenon has been
called the “negative leading indicator” property. This effect is problematic for most mainstream macroeconomic models, and it appears to be no less so in the present case. A similar conclusion is reached considering the correlations of employment with lagged inflation.

4.7 What Changed after 1979?

Figure 6 displays the unconditional (“smoothed”) estimates of the model’s shocks for the benchmark parameterization.

Consistent with results from the variance decomposition, the markup shock can be seen to mimic the business cycle as represented in the employment data.

The estimates of the policy and sunspot shocks are suggestive of the effects of time variation of variance, corroborating the emphasis on such phenomena by Sims.
and Zha (2006). Such volatility appears likely to have peaked around 1980 or 1981.

But if a behavioral sea change is to be interpreted in the data, then the model attributes this change to a sequence of large positive (persistent) IS shocks between 1980:IV and 1981:II.\footnote{The earliest of these dates coincided with large positive policy and sunspot shocks. These shocks are viewed as less important owing primarily to low persistence.}

To try to understand the nature of this shift of the IS relationship, it is useful first to recognize that the IS relationship (11) implies a decomposition of the expected (i.e., “ex ante”) real interest rate as the difference between expected employment growth and an “IS residual”:

\[
\rho_t \equiv R_t - E_t \Pi_{t+1} = a_t - E_t a_{t+1} - h_t + E_t h_{t+1}
\]

the estimate of this quantity obtained from the benchmark parameterization is shown as the thicker line in Figure 7. In the present model, this “residual” is equal to expected growth of the preference shock, which is proportional to the preference shock itself according to (2). Furthermore, it bears emphasis that, allowing for substitution of employment growth by growth of the “output gap”, such a decomposition is implied by any in a large class of models that includes most New Keynesian specifications.\footnote{The IS residual has been allowed diverse interpretations. Rotemberg and Woodford (1997) suggest the examples of government spending shocks or consumption purchases by liquidity constrained consumers with exogenous income streams.}

Second, my estimate of the time series of the expected real interest rate corroborates findings of other careful studies of this object by Antoncic (1986) and Garcia and Perron (1996), and is in line with a measure of the ex post real rate (shown as the thin line in Figure 7).

Antoncic (1986) interprets her findings as evidence contrary to the hypothesis that systematic changes in monetary policy after October 1979 explain the subsequent increase of the volatility and the level of real interest rates. She dates the rise of volatility to April 1980, and points to a particularly sharp increase her estimate of the ex ante real interest rate starting in November 1980. Similarly, Garcia and Perron (1996) identify an increase of the mean of the real interest rate process in the middle of 1981, and suggest that the finding “is more in line with a federal budget deficit explanation than with the change of monetary policy that occurred in the end of 1979”.

Reiterating the point emphasized above, it seems that most any model utilizing...
Figure 7: Real interest rate.
a simple IS relationship must deliver large IS residuals or large estimates of expected employment or output growth for these quarters if it is to be consistent with estimates of the expected real interest rate. Given the situation of these quarters on the brink of the recession that began in 1981:III, estimates suggesting the latter would be less plausible. This suggests that, independent of stickiness of prices, such models must suggest an important—perhaps dominant—role for an IS shock in the explanation for the behavior of real interest rates after 1980.

5 Conclusions

It is well-known that, in the context of a standard formulation of the New Keynesian sticky price model, the stance of monetary policy with respect to inflation is an important determinant of the existence and uniqueness of rational expectations equilibria. In particular, a strong response ("active" policy) typically implies a unique equilibrium with forward-looking inflation, and a weak response ("passive" policy) may admit other equilibria. This paper has argued that equilibria featuring backward-looking inflation may be more consistent with observation and intuition. This view is at odds with the focus in the literature.

I began by showing how, under active policy, forward-looking equilibria exhibit a basic negative autocorrelation in inflation, and that a high degree of price stickiness is necessary to patch over this counterfactual implication. This observation affords some perspective on the adequacy of the model with respect to its ability to reproduce the persistence in inflation data.\footnote{See Fuhrer and Moore (1995) and Nelson (1998).} In contrast, backward-looking equilibria that exist under passive policy show intrinsic positive autocorrelation even under fully flexible prices.

This analysis is moot if policy has been active, as much of the literature has presumed. But maximum likelihood estimates of the structural model are not supportive of this presumption. For every subsample of data that I examined, including two that begin after the perceived shift of monetary policy in 1979, the data prefer the explanation of passive policy under an equilibrium with backward-looking inflation. Moreover, for my preferred specification of the policy rule, the parameters of monetary policy show substantial stability over the period 1959-2001.

Benchmark parameter estimates also do not show a significant role for price stickiness. Given the important role of price stickiness in the determination of inflation persistence under forward-looking equilibria, my results suggest that estimates of large price adjustment costs in the literature may be a manifestation of misspeci-
fication associated with the restriction to the determinacy region of the parameter space.

Extra-fundamental uncertainty seems to contribute to uncertainty of forecasts of inflation at short horizons, but this effect tapers to 3.2% in the long run. Such sunspots have essentially no effect on other variables.

So what explains the perception of starkly different behavior of the relevant variables after the early 1980s? My estimates focus attention on a sequence of large shocks to the IS relationship between the third quarter of 1980 and the second quarter of 1981; this is equivalent to a sharp increase in expected (ex ante) real interest rates, which is, in turn, consistent with an increase of ex post real interest rates in the data.

Thus, the evidence points to shocks to the real side of the economy at the root of these perceptions. But as I emphasized in the previous section, a similar interpretation must derive from any model incorporating the simple IS relationship in application to this data. In particular, the essential step is not at the level of the specification of the nature of equilibrium, but rather it is merely the insistence that the structure of the IS equation remains unaltered across the episode. These results suggest that the emphasis on monetary policy in explaining these changes may be unwarranted.

6 Appendix A

This appendix shows how equations (11) and (12) may be derived from the model described in the text.

First-order conditions for the optimal choices of $c_t, h_t, m_t$, and $b_t$ by the household can be seen to imply that

$$w_t = \gamma c_t$$

and

$$a_t c_t^{-1} = \beta R_t E_t \frac{a_{t+1} c_{t+1}^{-1}}{\Pi_{t+1}},$$

where $\Pi_{t+1} \equiv P_{t+1}/P_t$. It is easily seen using (9), (10), and the non-stochastic steady-state relationship

$$1 = \beta Rg/\Pi$$

that (11) is a straightforward linearization of the Euler equation (24) about this point.

The nominal profit of intermediate goods producer $i$ in period $t$ can be seen to
be

\[
\hat{d}_t (i) = \hat{P}_t (i) \hat{y}_t (i) - P_t w_t h_t (i) - \frac{\phi}{2} \left[ \frac{\hat{P}_t (i)}{\Pi \hat{P}_{t-1} (i)} - 1 \right]^2 y_t \\
= P_t \left\{ \left( \frac{\hat{P}_t (i)}{P_t} \right)^{1-\theta_t} y_t - \left( \frac{\hat{P}_t (i)}{P_t} \right)^{-\theta_t} w_t y_t - \frac{\phi}{2} \left[ \frac{\hat{P}_t (i)}{\Pi \hat{P}_{t-1} (i)} - 1 \right]^2 y_t \right\},
\]

where the second line uses (6) and (8). Dividend distributions at time \( t \) facilitate the household’s purchase of consumption at time \( t \), so that the firm’s market valuation may be assessed by discounting time \( t \) cash flows using the household’s stochastic discount factor for cash, which is

\[
\varpi_t \equiv \frac{\beta^t a_t c_t^{-1}}{a_0 c_0^{-\sigma}} \left( \prod_{r=0}^{t} \Pi_r \right)^{-1},
\]

where \( \Pi_{t+1} \equiv P_{t+1}/P_t \) (and \( P_{-1} \) is assumed to be given). Accordingly, the firm’s problem can be described as that of choosing \( \{ \hat{P}_t (i) \}_{t=0}^{\infty} \) to maximize

\[
E_0 \sum_{t=0}^{\infty} \varpi_t \hat{d}_t (i)
\]

taking \( \hat{P}_{-1} (i) \) as given.

The intermediate goods firms’ first-order condition is

\[
E_t \left[ \frac{\beta^t a_t c_t^{-1}}{a_0 c_0^{-\sigma}} \left( \prod_{r=0}^{t} \Pi_r \right)^{-1} \right] \left\{ (1 - \theta_t) \left[ \frac{\hat{P}_t (i)}{P_t^{1-\theta_t}} \right]^{-\theta_t} y_t + \theta_t \left[ \frac{\hat{P}_t (i)}{P_t^{-\theta_t}} \right]^{-\theta_t-1} w_t y_t \right\}\
\]

\[
- \phi \left[ \frac{\hat{P}_t (i)}{\Pi \hat{P}_{t-1} (i)} - 1 \right] \frac{y_t}{\Pi \hat{P}_{t-1} (i)}
\]

\[
+ E_t \left\{ \frac{\beta^{t+1} a_{t+1} c_{t+1}^{-1}}{a_0 c_0^{-\sigma}} \left( \prod_{r=0}^{t+1} \Pi_r \right)^{-1} \phi \left[ \frac{\hat{P}_{t+1} (i)}{\Pi \hat{P}_t (i)} \right]^{-1} \phi \left[ \frac{\hat{P}_{t+1} (i)}{\Pi \hat{P}_t (i)} - 1 \right] \frac{y_{t+1} \hat{P}_{t+1} (i)}{\Pi \hat{P}_t (i)^2} \right\} = 0.
\]
Now using \( \hat{P}_t(i) = P_t \), multiplying by
\[
\left( \prod_{\tau=0}^{t} \Pi_{\tau} \right) \left( \frac{a_0 c_0^{-1}}{\beta' a_t c_t^{-1}} \right),
\]
and using the household’s Euler equation, we have after cancelling terms and re-labeling
\[
\left\{ \frac{(1 - \theta_t) y_t}{P_t} + \frac{\theta_t w_t y_t}{P_t Z_t} - \phi \left( \frac{\Pi_t}{\Pi} - 1 \right) \frac{y_t}{\Pi P_{t-1}} \right\} + \frac{1}{R_t} E_t \left\{ \phi \left( \frac{\Pi_{t+1}}{\Pi} - 1 \right) \frac{y_{t+1} \Pi_{t+1}}{\Pi P_t} \right\} = 0.
\]
Now multiply by \( P_t/y_t \), replace \( y_t/Z_t \) with \( h_t \), and replace \( w_t \) with \( \gamma c_t \); we have
\[
\left\{ (1 - \theta_t) + \frac{\gamma \theta_t c_t h_t}{y_t} - \phi \left( \frac{\Pi_t}{\Pi} - 1 \right) \frac{\Pi_t}{\Pi} \right\} + \frac{1}{R_t} E_t \left\{ \phi \left( \frac{\Pi_{t+1}}{\Pi} - 1 \right) \left( \frac{\Pi_{t+1}}{\Pi} \right) \left( \frac{y_{t+1}}{y_t} \right) \right\} = 0.
\]
Finally, use the resource constraint to replace \( c_t/y_t \),
\[
(1 - \theta_t) + \gamma \theta_t h_t \left[ 1 - \phi \left( \frac{\Pi_t}{\Pi} - 1 \right)^2 \right] - \phi \left( \frac{\Pi_t}{\Pi} - 1 \right) \frac{\Pi_t}{\Pi}
+ \frac{1}{R_t} E_t \left\{ \phi \left( \frac{\Pi_{t+1}}{\Pi} - 1 \right) \left( \frac{\Pi_{t+1}}{\Pi} \right) \left( \frac{y_{t+1}}{y_t} \right) \right\} = 0.
\]
In the non-stochastic steady-state, this equation becomes
\[
\theta - 1 = \gamma \theta h.
\]
Using this and some algebra, the equation may be approximated by the log-linearization
\[
\frac{\phi g}{\theta - 1} E_t \hat{\Pi}_{t+1} = \frac{\phi}{\theta - 1} \hat{\Pi}_t - \hat{h}_t + \hat{\theta}_t,
\]
where\(^{25}\)
\[
\hat{\theta}_t \equiv \frac{\theta_t - \theta}{\theta (\theta - 1)}.
\]
\(^{25}\)The special form for the linearized representation of \( \theta_t \) is a manifestation of the fact that \( \theta_t - 1 \), rather than \( \theta_t \), is assumed to be log-normal.
Note from (26) that, for the $\phi = 0$ case, the intermediate goods producer chooses

$$\hat{P}_t(i) = \left(\frac{\theta_t}{\theta_t - 1}\right) \frac{P_tw_t}{Z_t}.$$

Thus, as shown by Ireland (2004), $\theta_t / (\theta_t - 1)$ is the firm’s markup over marginal cost in this case, and innovations in $\theta_t$ may be interpreted as (negative) markup shocks.

**Appendix B**

In this appendix, I discuss solutions of the equation

$$E_t\hat{\Pi}_{t+1} - \rho_R E_{t-1}\hat{\Pi}_t - (1 - \rho_R) \nu_\pi \hat{\Pi}_{t-1} = x_t.$$  \hspace{1cm} (27)

We may apply the factorization approach of Sargent (1987).26 Begin by taking expectations with respect to the time $t - 1$ information set,

$$E_{t-1}\hat{\Pi}_{t+1} - \rho_R E_{t-1}\hat{\Pi}_t - (1 - \rho_R) \nu_\pi \hat{\Pi}_{t-1} = E_{t-1}x_t,$$

and write this as

$$[B^{-1} - \rho_R - (1 - \rho_R) \nu_\pi B] E_{t-1}\hat{\Pi}_t = E_{t-1}x_t$$

where $B$ is the “backshift operator” that acts on time series objects within an information set. Now apply the backshift operator to both sides to get

$$[1 - \rho_R B - (1 - \rho_R) \nu_\pi B^2] E_{t-1}\hat{\Pi}_t = E_{t-1}x_{t-1}.$$

Next, factor the polynomial on the LHS as

$$(1 - \lambda_1 B)(1 - \lambda_2 B) E_{t-1}\hat{\Pi}_t = E_{t-1}x_{t-1},$$  \hspace{1cm} (28)

where $\lambda_1 + \lambda_2 = \rho_R$ and $\lambda_1 \lambda_2 = - (1 - \rho_R) \nu_\pi$; that is (w.l.o.g.),

$$\lambda_1 = \frac{\rho_R}{2} - \sqrt{\left(\frac{\rho_R}{2}\right)^2 + (1 - \rho_R) \nu_\pi}.$$

---

26See pages 307-8 of Sargent (1987); Blanchard and Fischer also provide a clear exposition of the approach.
and
\[ \lambda_2 = \frac{\rho_R}{2} + \sqrt{\left(\frac{\rho_R}{2}\right)^2 + (1 - \rho_R) \nu_\pi}. \]

Under the assumptions that \( \rho_R, \nu_\pi \in [0, 1) \), a meaningful solution is obtained only if \( |\lambda_1| < 1 \); if not, then the system has no stable solution with \( \Pi_{t-1} \) predetermined at \( t \) for generic shocks \( x_t \). Noting that \( \lambda_1 \leq 0 \) under these assumptions, this condition is satisfied as long as
\[ \nu_\pi < \frac{1 + \rho_R}{1 - \rho_R}. \]

To see this, start with
\[ \lambda_1 = \frac{\rho_R}{2} - \sqrt{\left(\frac{\rho_R}{2}\right)^2 + (1 - \rho_R) \nu_\pi} > -1 \]
or
\[ -\sqrt{\rho_R^2 + 4 (1 - \rho_R) \nu_\pi} > -(2 + \rho_R). \]

Now squaring each side (which means multiplying each side by a negative number), we deduce
\[ \rho_R^2 + 4 (1 - \rho_R) \nu_\pi < 4 + 4 \rho_R + \rho_R^2, \]
which implies the result.

Next note that \( \lambda_2 > 1 \) if and only if \( \nu_\pi > 1 \). To see this, start with
\[ \lambda_2 = \frac{\rho_R}{2} + \sqrt{\left(\frac{\rho_R}{2}\right)^2 + (1 - \rho_R) \nu_\pi} > 1 \]
or
\[ \sqrt{\rho_R^2 + 4 (1 - \rho_R) \nu_\pi} > 2 - \rho_R. \]

Since both sides are positive, squaring both sides yields the equivalent statement
\[ \rho_R^2 + 4 (1 - \rho_R) \nu_\pi > 4 - 4 \rho_R + \rho_R^2, \]
which implies the result.

The important cases are now distinguished by the veracity of the condition \( \lambda_2 > 1 \), which holds if and only if \( \nu_\pi > 1 \). If so, then there is a unique stable solution that may be obtained as follows.\(^{27}\) First, we solve the “unstable root” \( \lambda_2 \) forward in (28)

\(^{27}\) See Blanchard and Kahn (1980).
to obtain
\[(1 - \lambda_1 B) E_{t-1}\hat{\Pi}_t = \frac{-\lambda_2^{-1}B^{-1}}{1 - \lambda_2^{-1}B^{-1}}E_{t-1}x_{t-1}\]
or
\[E_{t-1}\hat{\Pi}_t = \lambda_1\hat{\Pi}_{t-1} - \lambda_2^{-1}\sum_{j=0}^{\infty} \lambda_2^{-j}E_{t-1}x_{t+j}.\]

Now substitute this expression and the same expression shifted forward one period into (27) to obtain
\[\left[\lambda_1\hat{\Pi}_t - \lambda_2^{-1}\sum_{j=0}^{\infty} \lambda_2^{-j}E_{t}x_{t+j+1}\right] - \rho_R \left[\lambda_1\hat{\Pi}_{t-1} - \lambda_2^{-1}\sum_{j=0}^{\infty} \lambda_2^{-j}E_{t-1}x_{t+j}\right] - (1 - \rho_R)v_t\hat{\Pi}_{t-1} = x_t\]
or
\[\hat{\Pi}_t = \left[\rho_R + (1 - \rho_R)\frac{\nu_t}{\lambda_1}\right]\hat{\Pi}_{t-1} + \frac{1}{\lambda_1\lambda_2}\sum_{j=0}^{\infty} \lambda_2^{-j}E_{t}x_{t+j+1} - \frac{1}{\lambda_1\lambda_2}\sum_{j=0}^{\infty} \lambda_2^{-j}E_{t-1}x_{t+j} + \frac{1}{\lambda_1}x_t.\]

Finally, using the fact that
\[\lambda_1^2 - \lambda_1\rho_R + (1 - \rho_R)\nu_t = 0,\]
we have
\[\hat{\Pi}_t = \lambda_1\hat{\Pi}_{t-1} + \frac{1}{\lambda_1\lambda_2}\sum_{j=0}^{\infty} \lambda_2^{-j}E_{t}x_{t+j+1} - \frac{1}{\lambda_1\lambda_2}\sum_{j=0}^{\infty} \lambda_2^{-j}E_{t-1}x_{t+j} + \frac{1}{\lambda_1}x_t.\]

Under the assumptions we have made about the components of \(x_t\), this can be re-written as
\[\hat{\Pi}_t = \lambda_1\hat{\Pi}_{t-1} - \frac{1}{\lambda_1}\left[(1 - \rho_a)\frac{(\rho_a - \rho_R)}{\lambda_2(1 - \lambda_2\rho_a)} + 1 - \rho_a\right]\hat{a}_t + \frac{1}{\lambda_1}\left[(1 - \rho_a)\frac{(\rho_a - \rho_R)}{\lambda_2(1 - \lambda_2\rho_a)} + \rho_R(1 - \rho_a)\right]\hat{a}_{t-1}\]
\[+ \frac{1}{\lambda_1}\left[(1 - \rho_\theta)\frac{(\rho_\theta - \rho_R)}{\lambda_2(1 - \lambda_2\rho_\theta)} + (1 - \rho_R)\nu_h\right] + 1 - \rho_\theta\right]\hat{\theta}_t\]
\[\frac{1}{\lambda_1}\left[(1 - \rho_\theta)\frac{(\rho_\theta - \rho_R)}{\lambda_2(1 - \lambda_2\rho_\theta)} + \rho_R(1 - \rho_\theta) - (1 - \rho_R)\nu_h\right] \hat{\theta}_{t-1}\]
\[+ \left[1 + \frac{\rho_v}{1 - \lambda_2\rho_v}\right]v_t - \frac{\rho_v}{1 - \lambda_2\rho_v}v_{t-1}.\]
References


