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## Monetary discretion, pricing complementarity and dynamic multiple equilibria

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No. 2004/22

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Prof. Dr. Jan Pieter Krahenen

A handwritten signature in black ink, appearing to read "Volker Wieland".

Prof. Volker Wieland, Ph.D.



## **Monetary Discretion, Pricing Complementarity and Dynamic Multiple Equilibria\***

Robert G. King and Alexander L. Wolman

March 2004

### **Abstract:**

In a plain-vanilla New Keynesian model with two-period staggered price-setting, discretionary monetary policy leads to multiple equilibria. Complementarity between the pricing decisions of forward-looking firms underlies the multiplicity, which is intrinsically dynamic in nature. At each point in time, the discretionary monetary authority optimally accommodates the level of predetermined prices when setting the money supply because it is concerned solely about real activity. Hence, if other firms set a high price in the current period, an individual firm will optimally choose a high price because it knows that the monetary authority next period will accommodate with a high money supply. Under commitment, the mechanism generating complementarity is absent: the monetary authority commits not to respond to future predetermined prices. Multiple equilibria also arise in other similar contexts where (i) a policymaker cannot commit, and (ii) forward-looking agents determine a state variable to which future policy responds.

**JEL Classification:** E5, E61, D78

**Keywords:** Monetary Policy, Discretion, Time-Consistency, Multiple Equilibria, Complementarity

\*rking@bu.edu, Boston University and alexander.wolman@rich.frb.org, Federal Reserve Bank of Richmond. This paper is an outgrowth of the authors' work in progress with Aubhik Khan, available at <http://www.rich.frb.org/pubs/wpapers/pdfs/wp01-8.pdf>; it does not necessarily represent the views of the Federal Reserve System, the Federal Reserve Board, or the Federal Reserve Bank of Richmond. We have benefited from conversations with Russell Cooper, Huberto Ennis, Mark Gertler, Andreas Horn-stein, Olivier Jeanne, John Leahy and Henry Siu, and from presentations at Harvard, Iowa, MIT, the New York Fed, UQAM, Western Ontario, Wharton, York, the conference on Dynamic Models at the Bank of Canada, July 2003, and the International Research Forum on Monetary Policy, November 2003.

### **Non-technical summary**

In the debate over rules versus discretion for monetary policy, the primary argument against discretion has been that it leads to higher average inflation than is optimal with commitment. In the consensus basic model which has developed following Kydland and Prescott [1977] and Barro and Gordon [1983], the discretionary monetary authority seeks to produce unexpected inflation to stimulate real output, which is inefficiently low because of distortions in the economy. But since it cannot fool agents in rational expectations equilibrium, the discretionary monetary authority produces expected inflation that has a negligible real effect on output, while imposing other costs on the economy.

By contrast, this paper provides an example of a different, potentially adverse, consequence of discretionary monetary policy: it can lead to multiple equilibria and, thus, to the possibility of endogenous fluctuations in inflation and real activity that are not related to the economy's fundamentals. We illustrate this possibility within a simple dynamic macroeconomic model that has important New Keynesian features: (i) monopolistic competition, making output inefficiently low; and (ii) a staggered pricing structure in which firms set nominal prices that must be held fixed for two periods. These two features give the monetary authority some leverage over real activity.

In this simple setting, the multiplicity of equilibria derives from interaction between two features of the economy. First, firms adopt forward-looking pricing rules because their nominal prices are held fixed for two periods. In choosing a price, firms in the current period need to form expectations about the behavior of the monetary authority – and firms – in the next period. A higher future money supply leads to a higher future nominal marginal cost, which raises the optimal price for a firm in the current period. Second, under discretion, the monetary authority takes as given prices set in previous periods in determining its choice of the money stock in each period. Since its concern is to maximize the welfare of the representative agent, which depends on real variables, it chooses a money stock that is proportional to the price set by firms in the previous period, which we call a homogenous money stock rule.

The combination of forward-looking pricing with discretionary policy leads to complementarity between the price-setting actions of firms: if all other firms set a higher price in the current period, the monetary authority will set a higher money supply in the subsequent period, raising the desired price for a single firm in the current period.

We show that this policy-induced complementarity implies that there are typically two private-sector equilibria which can prevail at any point in time and two steady-state

equilibria. In general, there is one equilibrium in which firms expect small adjustments and the newly set price is relatively close to the price that firms set last period. But there is another in which the adjusting firms make a much larger adjustment.

Because this multiplicity of equilibria arises for arbitrary homogenous monetary policies, it also arises with an optimizing monetary authority who cannot commit to future actions. We begin by considering settings of perfect foresight, in which the monetary authority and private agents each assume that only one of the two types of private sector equilibria will occur. We show that there are two steady-state discretionary equilibria, one with low inflation bias and one with high inflation bias. It is notable that the complementarity which generates multiple equilibria is entirely due, in our model, to the nature of monetary policy under discretion. That is: our specification of preferences and the labor market is such that there is no complementarity in the price-setting behavior of firms if the central bank maintains a fixed nominal money stock. Our setup thus highlights the role of discretionary monetary policy in generating complementarity.

While our results concern the interaction between a monetary policymaker and a forward-looking private sector that sets prices for only two periods, they are indicative of a more general phenomenon, both in the context of monetary policy and in other areas of economics. The necessary features for the kind of phenomenon we describe are as follows: (i) a policymaker that cannot commit to future actions, and (ii) forward-looking private agents whose current actions determine a state-variable to which the policymaker responds in the future. These features seem quite widespread, suggesting that lack of commitment may be an important cause of economic instability.

# 1 Introduction

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In this simple setting, the multiplicity of equilibria derives from interaction between two features of the economy. First, firms adopt *forward-looking pricing rules* because their nominal prices are held fixed for two periods. In choosing a price, firms in the current period need to form expectations about the behavior of the monetary authority – and firms – in the next period. A higher future money supply leads to a higher future nominal marginal cost, which raises the optimal price for a firm in the current period. Second, under discretion, the monetary authority takes as given prices set in previous periods in determining its choice of the money stock in each period. Since its concern is to maximize the welfare of the representative agent, which depends on real variables, it chooses a money stock that is proportional to the price set by firms in the previous period, which we call a *homogenous money stock rule*.

The combination of forward-looking pricing with discretionary policy leads to *complementarity* between the price-setting actions of firms: if all other firms set a higher price in the current period, the monetary authority will set a higher money supply in the subsequent period, raising the desired price for a single firm in the current period.

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There is a rich literature on the importance of commitment for monetary policy. In section 6 we relate our analyses to three branches of the existing literature. The first comprises the seminal works of Kydland and Prescott [1977] and Barro and Gordon [1983]; they studied reduced-form linear models in which the policymaker had quadratic preferences, and emphasized that discretion led to inflation bias. The second branch is associated with the recent optimizing sticky-price models, which have typically been analyzed using LQ approximations. The emphasis in this work has been on inflation bias and stabilization bias. Finally, Albanesi, Chari and Christiano [2003] have shown that discretion leads to multiple equilibria in a different kind of sticky price model – one without the endogenous state variables which play such a crucial role here.

While our results concern an interaction between a monetary policymaker and a forward-looking private sector that sets prices for only two periods, they are indicative of a more general phenomenon, both in the context of monetary policy and in other areas of economics. In section 7, we discuss some empirical implications of our model, consider the consequences of extending it to multiple periods of price-setting, and describe other potential settings in which similar phenomena might arise. Section 8 concludes.



## 2 Model

The model economy that we study is a particular fully articulated “New Keynesian” framework, featuring monopolistic competition and nominal prices which are fixed for two periods. There is staggered pricing, with one-half of a continuum of firms adjusting price in each period. Since all of the firms have the same technology and face the same demand conditions, it is natural to think of all adjusting firms as choosing the same price. We impose this symmetry condition in our analysis.

There are many different types of New Keynesian models, which differ in terms of their implications for the extent of complementarity in price-setting. Our model assumes that (i) there is a constant elasticity demand structure originating from a Dixit-Stiglitz aggregator of differentiated products; (ii) there is a centralized labor market so that the common marginal cost for all firms is powerfully affected by aggregate demand; and (iii) preferences for goods and leisure display exactly offsetting income and substitution effects of wage changes, as is common in the literature on real business cycles. Kimball [1995] and Woodford [2002] have stressed that these assumptions make it difficult to generate complementarity between price-setters when there is an exogenous money stock. As we will, see our model has exactly zero complementarity in this situation. From our perspective, this is a virtue because it highlights the importance of the policy-based complementarity that arises from monetary policy under discretion.

### 2.1 Households

There is a representative household, which values consumption ( $c_t$ ) and leisure ( $l_t$ ) according to a standard time separable expected utility objective,

$$E_t\left\{\sum_{j=0}^{\infty}\beta^ju(c_{t+j},l_{t+j})\right\} \quad (1)$$

with  $\beta$  being the discount factor. We assume that the momentary utility function takes the form

$$u(c_t,l_t)=\log(c_t)+\chi l_t \quad (2)$$

which implies that there are exactly off-setting income and substitution effects of wage changes. It also has some other convenient implications that we describe later.

As is standard in the analyses of imperfect competition macro models that follow Blanchard and Kiyotaki [1987] and Rotemberg [1987], we assume that consumption is an

aggregate of a continuum of individual goods,  $c_t = [\int_0^1 c_t(z)^{(\varepsilon-1)/\varepsilon} dz]^{\varepsilon/(\varepsilon-1)}$ . Households distribute their expenditure efficiently across these goods, resulting in constant-elasticity demands for individual products from each of the two types of firms which they will encounter in the equilibrium below:

$$c_{j,t} = \left( \frac{P_{j,t}}{P_t} \right)^{-\varepsilon} c_t, \quad j = 0, 1. \quad (3)$$

The subscript  $j$  in (3) denotes the age of the nominal price, so that  $P_{0,t}$  is the price set by firms in period  $t$  and  $P_{1,t}$  is the price set by firms one period previously ( $P_{1,t} = P_{0,t-1}$ ). Likewise,  $c_{j,t}$  is the period- $t$  demand for goods produced by a firm that set its price in period  $t - j$ . The price level which enters in these demands takes the form

$$P_t = \left[ \frac{1}{2} P_{0,t}^{1-\varepsilon} + \frac{1}{2} P_{1,t}^{1-\varepsilon} \right]^{\frac{1}{1-\varepsilon}}. \quad (4)$$

We assume that households also hold money to finance expenditure, according to

$$M_t = \int_0^1 P_t(z) c_t(z) dz \quad (5)$$

so that our model imposes a constant, unit velocity, in common with many macroeconomic analyses.<sup>1</sup> We adopt this specification because it allows us to abstract from all the wealth and substitution effects that normally arise in optimizing models of money demand, so as to focus on the consequences of price-stickiness. With constant-elasticity demands for each good, the money-demand specification in (5) implies

$$M_t = P_t c_t. \quad (6)$$

Since this is a representative agent model and since no real accumulation is possible given the technologies described below, we are not too explicit about the consumption-saving aspect of the household's problem; it will be largely irrelevant in general equilibrium except for asset-pricing. We simply assume that there is a Lagrange multiplier that takes the form

$$\lambda_t = \frac{\partial u(c_t, l_t)}{\partial c_t} = \frac{1}{c_t}, \quad (7)$$

and that households equate the marginal rate of substitution between leisure and consumption to the real wage rate prevailing in the competitive labor market, i.e.,

$$w_t = \frac{\partial u(c_t, l_t) / \partial l_t}{\partial u(c_t, l_t) / \partial c_t} = \chi c_t. \quad (8)$$

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<sup>1</sup>We think of this quantity equation as the limiting version of a standard money demand function which occurs as the own return on money is raised toward the nominal interest rate (see King and Wolman [1999] for some additional discussion).

In each case, the second equality indicates the implications of the specific utility function introduced above.

## 2.2 Firms

Firms produce output according to a linear technology, where for convenience we set the marginal product of labor to one. So, for each type of firm, the production function is

$$c_{j,t} = n_{j,t}. \quad (9)$$

This implies that real marginal cost is unrelated to the scale of the firm or its type and is simply

$$\psi_t = w_t$$

and that nominal marginal cost is  $\Psi_t = P_t \psi_t = P_t w_t$

Much of our analysis will focus on the implications of efficient price-setting by the monopolistically competitive firm. The adjusting firms in period  $t$  are assumed to set prices so as to maximize the expected present discounted value of their revenues, using the household's marginal utility as a (possibly stochastic) discount factor. That is, they choose  $P_{0,t}$  to maximize their market value,

$$[\lambda_t(P_{0,t} - \Psi_t)c_{0,t} + \beta E_t \lambda_{t+1} \frac{P_t}{P_{t+1}} (P_{0,t} - \Psi_{t+1})c_{1,t+1}].$$

As monopolistic competitors, firms understand that  $c_{0,t} = (\frac{P_{0,t}}{P_t})^{-\varepsilon} c_t$  and that  $c_{1,t+1} = (\frac{P_{0,t}}{P_{t+1}})^{-\varepsilon} c_{t+1}$ , but take  $c_t, P_t, c_{t+1}$  and  $P_{t+1}$  as not affected by their pricing decisions. The efficient price must accordingly satisfy

$$P_{0,t} = \frac{\varepsilon}{\varepsilon - 1} \frac{P_t^{\varepsilon-1} \Psi_t + \beta E_t (P_{t+1}^{\varepsilon-1} \Psi_{t+1})}{P_t^{\varepsilon-1} + \beta E_t (P_{t+1}^{\varepsilon-1})}, \quad (10)$$

where we again give the result under the specific momentary utility function. In fact, this reveals one motivation for the form of the particular utility function chosen. In general, both aggregate demand ( $c_t$ ) and the discount factor ( $\lambda_t$ ) would appear in (10), but our choice of a utility function that is logarithmic in consumption means that these two effects exactly cancel out. With perfect foresight, the pricing equation can be written compactly as

$$P_{0,t} = \frac{\varepsilon}{\varepsilon - 1} [(1 - \theta_{t,t+1}) \Psi_t + \theta_{t,t+1} \Psi_{t+1}]; \quad (11)$$

the optimal price is a constant markup  $(\varepsilon/(\varepsilon - 1))$  over a weighted average of nominal marginal cost over the two periods, where the weight on the future is

$$\theta_{t,t+1} = \frac{\beta \lambda_{t+1} c_{t+1} P_{t+1}^{\varepsilon-1}}{\lambda_t c_t P_t^{\varepsilon-1} + \beta \lambda_{t+1} c_{t+1} P_{t+1}^{\varepsilon-1}} = \frac{\beta P_{t+1}^{\varepsilon-1}}{P_t^{\varepsilon-1} + \beta P_{t+1}^{\varepsilon-1}}. \quad (12)$$

The weights on current and future nominal marginal cost represent the shares of marginal revenue associated with the current and future periods.

### 2.3 Defining Complementarity in Price Setting

The standard definition of complementarity – contained, for example, in Cooper and John [1988] – is that the optimal action of one decision-maker is increasing in the actions of other similar decision-makers. In our context, we are interested in complementarity in price-setting in equation (11). The left-hand side of this expression is the action of the particular decision-maker under study: the optimal price of an individual monopolistically competitive firm that is currently making a price adjustment. Other monopolistically competitive firms are also simultaneously adjusting prices: these firms take an action  $P_{0,t}$  that influences the right-hand of (11). The price chosen by the representative adjusting firm influences the price level directly because  $P_t = [\frac{1}{2}P_{0,t}^{1-\varepsilon} + \frac{1}{2}P_{1,t}^{1-\varepsilon}]^{\frac{1}{1-\varepsilon}}$  and may also affect current nominal marginal cost. Given that prices are sticky, there can be real effects of variations in the price level, so that these could influence nominal marginal cost. Finally, the weights on the present and the future in (11) also depend on the price level. To determine whether there is complementarity, we must work through these mechanisms and determine the sign of the relevant partial derivative. The extent of complementarity will depend on the behavior of the monetary authority.

### 2.4 Timing

The sequence of actions within a period is as follows. In the first stage, the monetary authority chooses the money stock,  $M_t$ , taking as given  $P_{1,t}$ , the price set by firms in the previous period. In the second stage, adjusting firms set prices ( $P_{0,t}$ ). Simultaneously, wages are determined and exchange occurs in labor and goods markets.

There are two important consequences of these timing assumptions. First, since price-setters move after the monetary authority, they cannot be surprised by the monetary authority during the initial period that their price is in effect. Accordingly, the monetary authority faces an economy in which it can surprise some agents (those with pre-set prices)

but not others (those adjusting prices) within a period. This gives rise to a relative price distortion across firms in the discretionary equilibrium that we construct, which in turn means that there is an interior solution for the monetary authority's choice problem. If we reversed the timing order so that the monetary authority moved last, we conjecture that there would not be a discretionary equilibrium unless some other aspect of the economy were modified, such as allowing firms to reset their prices after paying an adjustment cost.<sup>2</sup> Second, the fact that the price-setters move after the monetary authority means that there is the potential for more than one equilibrium price to correspond to a given monetary policy action.

## 2.5 Complementarity with an exogenous money stock

We now consider a situation in which  $M_t = M_{t+1} = M$ . Under the assumptions of our model, it turns out to be easy to investigate the influence of other adjusting firm's actions, i.e., to compute the effect of  $P_{0,t}$  on the right-hand side of (11). The constant velocity assumption ( $P_t c_t = M_t$ ) and the particular utility function together imply  $\Psi_t = P_t w_t = P_t(\chi c_t)$ . Hence, equilibrium nominal marginal cost is exactly proportional to the money stock,  $\Psi_t = \chi M_t$ . Since the nominal money stock is assumed constant over time, nominal marginal cost is also constant over time and (11) becomes

$$P_{0,t} = \frac{\varepsilon}{\varepsilon - 1} \chi M.$$

This equilibrium relationship means that there is an exactly zero effect of  $P_{0,t}$  on the right-hand side: there is no complementarity in price-setting in this model when the nominal money supply is constant.

## 2.6 Summarizing the economy by $p_0$ and $m$

Under discretionary policy, the monetary authority will not choose to keep the nominal money supply constant. Therefore, the optimal pricing condition (11) will not simplify to a static equation. In general, however, equilibrium will be a function of just two variables: a measure of the price set by adjusting firms and a measure of monetary policy. We construct these variables by normalizing nominal prices and money by the single nominal

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<sup>2</sup>The nonexistence of a discretionary equilibrium is a feature of Ireland's [1997] analysis of a model in which all prices are set simultaneously, before the monetary authority determines the current money supply.

state variable in this economy, the price set by firms in the previous period ( $P_{1,t} = P_{0,t-1}$ ). Define the normalized money supply as

$$m_t = M_t/P_{1,t}, \quad (13)$$

and the normalized price set by adjusting firms in the current period as

$$p_{0,t} = P_{0,t}/P_{1,t}. \quad (14)$$

We can then express all variables of interest as functions of these two normalized variables. From (4), the normalized price level is a function of only  $p_{0,t}$  :

$$\frac{P_t}{P_{1,t}} = g(p_{0,t}),$$

where

$$g(p_{0,t}) \equiv \left[ \frac{1}{2} p_{0,t}^{1-\varepsilon} + \frac{1}{2} \right]^{\frac{1}{1-\varepsilon}}.$$

Aggregate demand is a function of both  $p_{0,t}$  and  $m_t$  :

$$c_t = c(p_{0,t}, m_t) \equiv \frac{m_t}{g(p_{0,t})}.$$

This follows from the money demand equation:

$$c_t = \frac{M_t}{P_t} = \frac{M_t}{P_{1,t}} \frac{P_{1,t}}{P_t} = \frac{m_t}{g(p_{0,t})}.$$

Further, since  $n_t = [\frac{1}{2}n_{0,t} + \frac{1}{2}n_{1,t}] = [\frac{1}{2}c_{0,t} + \frac{1}{2}c_{1,t}]$ , we can use the individual demands together to show that total labor input is also pinned down by  $p_{0,t}$  and  $m_t$  :

$$n_t = n(p_{0,t}, m_t) \equiv \frac{1}{2} \cdot c(p_{0,t}, m_t) \cdot [g(p_{0,t})]^\varepsilon \cdot (p_{0,t}^{-\varepsilon} + 1).$$

Leisure is the difference between the time endowment and labor input. Marginal cost is

$$\psi_t = w_t = \frac{\partial u(c_t, l_t)/\partial l_t}{\partial u(c_t, l_t)/\partial c_t} = \chi c_t = \psi(m_t, p_{0,t}).$$

Another variable of interest is the gross inflation rate,  $P_{t+1}/P_t$ . It is determined by current and future  $p_0$ :

$$\frac{P_{t+1}}{P_t} = \pi(p_{0,t}, p_{0,t+1}) \equiv \frac{g(p_{0,t+1})}{g(p_{0,t})} p_{0,t}. \quad (15)$$

This follows directly from writing the inflation rate as a ratio of normalized variables:

$$\frac{P_{t+1}}{P_t} = \frac{P_{t+1}/P_{0,t}}{P_t/P_{1,t}} \cdot \frac{P_{0,t}}{P_{1,t}} = \frac{g(p_{0,t+1})}{g(p_{0,t})} p_{0,t}.$$

In a steady state, there is thus a simple relationship between inflation and the relative price,  $\pi = p_0$ .

## 2.7 Two distortions and monetary policy

The monetary authority in this model faces two distortions that are present in the private economy and can be influenced by its actions. First, there is a *markup distortion* that represents the wedge between price and marginal cost: it has consequences similar to those of a tax on labor income. The markup is just the reciprocal of real marginal cost,

$$\mu_t = \frac{1}{\psi_t} = \frac{1}{w_t} = \frac{\partial u(c_t, l_t)/\partial c_t}{\partial u(c_t, l_t)/\partial l_t} = \frac{1}{\chi c_t}.$$

From the derivations above, the markup depends on  $p_{0,t}$  and  $m_t$ :  $\mu_t = g(p_{0,t})/(\chi m_t)$ . Second, there is a *relative price distortion* that represents a wedge between inputs and outputs:

$$n_t/c_t = \delta(p_{0,t}) \equiv \frac{1}{2} \cdot [g(p_{0,t})]^\varepsilon \cdot (p_{0,t}^{-\varepsilon} + 1).$$

The relative price distortion depends solely on  $p_{0,t}$ . It takes on a value of unity at  $p_{0,t} = 1$  (this would be the case in a zero inflation steady state) and is higher for other values of  $p_{0,t}$ . The trade-off that the monetary authority typically faces between these two distortions is that choosing a higher money supply decreases the markup (good) and raises the relative price distortion (bad).

Just as we showed above that all real variables could be described in terms of  $p_0$  and  $m$ , the distortions can be described similarly. The summary role of  $p_0$  and  $m$ , together with the fact that at any point in time the monetary authority can choose  $m$  (i.e. choosing  $m$  in the current period is no different than choosing  $M$ ) has a strong implication for the analysis of discretionary monetary policy.<sup>3</sup> It implies that the level of the predetermined nominal price  $P_{1,t}$  does not restrict the outcomes a discretionary policymaker can achieve, as long as the monetary authority in future periods behaves in the same manner.<sup>4</sup>

We now analyze outcomes under monetary discretion, proceeding in three steps (with each a separate section of the paper). We begin by studying perfect foresight settings. In section 3, we detail the nature of perfect foresight private sector equilibria under a particular class of monetary policy rules. In section 4, we describe a full discretionary equilibrium – with optimization by the monetary authority—in which policy is shown to be in this class of rules. Finally, in section 5, we discuss stochastic discretionary equilibria.

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<sup>3</sup>It is important not to misinterpret the parenthetical statement: any choice of  $M_t$  can be replicated by choosing  $m_t = M_t/P_{1,t}$ . However, a *policy* of keeping  $M_t$  constant is not the same as a policy of keeping  $m_t$  constant.

<sup>4</sup>If the future monetary authority paid attention to nominal levels, it might be optimal for the current monetary authority to do the same. We do not consider equilibria with this property.

### 3 Equilibrium with homogeneous policy

We begin by studying the nature of equilibrium price-setting  $(p_{0,t})$  given an arbitrary action by the monetary authority and given perfect foresight. We assume that the monetary authority adopts a policy rule of the form

$$M_t = m_t P_{0,t-1}, \quad (16)$$

where  $m_t$  is viewed as the policy variable. That is, the money supply is proportional to the prices that adjusting firms set one period ago with a constant of proportionality  $m_t$ . We call this a *homogenous monetary policy rule*. This form of monetary accommodation of past nominal variables is characteristic of optimal monetary policy under discretion, for the following reason. The monetary authority is concerned about the real variables that enter in private agents' utility. It takes past prices as given, and there is no mechanism by which the level of nominal predetermined prices necessarily constrains the behavior of a discretionary policymaker.<sup>5</sup> Thus, if we viewed  $M$  instead of  $m$  as the policy instrument, we would find that the optimizing monetary authority adjusted  $M_t$  proportionally to  $P_{1,t}$ , just as is specified in (16). It will economize slightly on notation and computation to view  $m_t$  as the policy instrument, and there is no loss in generality. In a discretionary equilibrium,  $m_t$  will be chosen to maximize welfare; in this section  $m_t$  is arbitrary.<sup>6</sup>

A homogenous money supply rule means that the future money supply depends on the price set by adjusting firms today,

$$M_{t+1} = m_{t+1} P_{0,t}.$$

Consequently, under homogeneous policy and using the preferences introduced above, it follows from the efficient price-setting condition (11) that the nominal price set by adjusting firms  $(P_{0,t})$  satisfies

$$P_{0,t} = \frac{\varepsilon \chi}{\varepsilon - 1} ((1 - \theta_{t,t+1}) m_t P_{1,t} + \theta_{t,t+1} m_{t+1} P_{0,t}) \quad (17)$$

in equilibrium. The derivation of (17) from (11) involves (i) using the fact that nominal marginal cost is  $\Psi_t = P_t \chi c_t$  given the specific utility assumption; (ii) using the money demand relationship  $(M_t = P_t c_t)$ ; and (iii) imposing the homogenous form of the monetary

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<sup>5</sup>The word “necessarily” appears because one could construct non-Markov equilibria in which all agents agreed that  $P_{1,t}$  did constrain the monetary authority. See previous footnote. We do not study such equilibria.

<sup>6</sup>By contrast, under commitment, the monetary authority commits *not* to respond to  $P_{1,t}$ , and the choice is over sequences of  $M_t$ . King and Wolman (1999) study optimal policy with commitment in the model used here.



policy rule ( $M_t = m_t P_{1,t}$ ). From (17), the normalized price set by adjusting firms ( $p_{0,t}$ ) satisfies

$$\begin{aligned} p_{0,t} &= \left( \frac{\varepsilon \chi}{\varepsilon - 1} \right) ((1 - \theta_{t,t+1}) m_t + \theta_{t,t+1} m_{t+1} p_{0,t}) \\ &\equiv r(p_{0,t}, m_t, p_{0,t+1}, m_{t+1}). \end{aligned} \quad (18)$$

The weight on future nominal marginal cost, which was defined in (12), can be written in terms of current and future normalized prices as

$$\theta(p_{0,t}, p_{0,t+1}) = \frac{\beta \pi(p_{0,t}, p_{0,t+1})^{\varepsilon-1}}{1 + \beta \pi(p_{0,t}, p_{0,t+1})^{\varepsilon-1}}. \quad (19)$$

where we are now explicit about how  $\theta_{t,t+1}$  depends on the present and the future. Equation (18) is a nonlinear difference equation in  $p_0$  and  $m$  that must be satisfied in a perfect foresight equilibrium with homogeneous policy.

We view  $p_{0,t}$  on the left-hand side of (18) as describing what an individual firm finds optimal given the actions of other price-setters and the monetary authority. On the right hand side,  $p_{0,t}$  then represents all other adjusting firms' pricing behavior, and the function on the right hand side represents the implications of those firms' behavior for the marginal revenues and costs of an individual firm. In other words,  $r(\cdot)$  is a *best-response function* for the individual firm. We restrict attention to symmetric equilibria, so that prices chosen by all adjusting firms are identical. We define complementarity in terms of a positive partial derivative of the response function with respect to its first argument. That is: with perfect foresight, there is complementarity if  $\partial r(p_{0,t}, m_t, p_{0,t+1}, m_{t+1}) / \partial p_{0,t} > 0$ .

In sections 3.2 and 3.3 below, we will make intensive use of the perfect-foresight best-response function (18). First, we will use it to describe point-in-time equilibria; this involves characterizing the fixed points for  $p_{0,t}$ , taking as given  $m_t, m_{t+1}$ , and  $p_{0,t+1}$ . Second, we will use it to determine the model's steady-state equilibria under constant arbitrary policy. That is, we will impose  $p_{0,t} = p_{0,t+1}$  and  $m_t = m_{t+1} = m$  and determine the equilibrium value(s) (fixed points) for  $p_0$ . Both of these exercises will then serve as inputs to our analysis of discretionary equilibria. There, (18) will summarize private sector equilibrium for any action that the monetary authority contemplates, under perfect foresight.<sup>7</sup> With uncertainty, (18) will not hold exactly, but the mechanisms discussed here will still be relevant.

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<sup>7</sup>If we impose  $m_t = m_{t+1}$  but allow  $p_{0,t}$  to differ from  $p_{0,t+1}$ , then (18) describes the dynamics of  $p_{0,t}$  for constant homogeneous policy. Such analysis might reveal interesting dynamics. However, it is not an input into our analysis of discretionary equilibrium.

### 3.1 Complementarity under homogeneous monetary policy

There are two mechanisms for complementarity in (17) and (18) that will be operative in our analysis of both point-in-time and steady-state equilibria. First, holding fixed the weights,  $P_{0,t}$  has a positive effect on the right-hand side in (17): it enters linearly with a coefficient of  $\left(\frac{\varepsilon\chi}{\varepsilon-1}\right)\theta_{t,t+1}m_{t+1}$ , which is positive because firms are forward-looking and the monetary authority raises nominal  $M_{t+1}$  proportionately with  $P_{0,t}$ . Hence the specification of monetary policy has introduced some complementarity into an economy in which it was previously absent.

Second, the weights in these expressions vary with the current price  $P_{0,t}$  (or its normalized counterpart  $p_{0,t}$ ). This additional channel plays an important role in our analysis. A reference value for the weight  $\theta_{t,t+1}$  is one-half, since (12) implies that the weight is  $\beta/(1+\beta)$  with  $\beta$  close to one if  $P_t = P_{t+1}$ . An upper bound on this weight is one: this is a situation where firms place full weight on the future. Increases in the weight raise the extent of the effect discussed above, i.e., they raise the coefficient  $\left(\frac{\varepsilon\chi}{\varepsilon-1}\right)\theta_{t,t+1}m_{t+1}$  that measures the extent of complementarity. The second mechanism is then that an increase in  $P_{0,t}$  (or its normalized counterpart  $p_{0,t}$ ) raises the weight on the future. This occurs because a firm's profits are not symmetric around its optimal price. As the firm's relative price rises, its profits decline gradually, asymptotically reaching zero as the price goes to infinity. By contrast, as the price falls, the firm's profits decline sharply toward zero and may even become highly negative if the firm is not allowed to shut down its operations.<sup>8</sup> Thus, when  $P_{0,t}$  increases for all other firms, future monetary accommodation – and the associated higher *nominal* price set by firms in the future – automatically lowers the firm's future relative price. The costliness of a low relative price leads the firm to put increased weight on future marginal cost.

### 3.2 Equilibrium analysis of steady states

To characterize steady-state equilibria for arbitrary constant, homogeneous monetary policies, we impose constant  $m$  and  $p_0$  on the right hand side of (18). Steady-state equilibria are fixed points of the resulting steady-state best-response function for  $p_0$ :

$$p_0 = \frac{\varepsilon\chi}{\varepsilon-1}m[1 - \theta(p_0, p_0) + \theta(p_0, p_0)p_0], \quad (20)$$

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<sup>8</sup>At this point in the analysis, we do not explicitly take into account the shut-down possibility. But, when we calculate discretionary equilibria, we do verify that the equilibria are robust to allowing firms to shut down.

with a weight on the future of

$$\theta(p_0, p_0) = \frac{\beta p_0^{\varepsilon-1}}{1 + \beta p_0^{\varepsilon-1}}. \quad (21)$$

Fixed points of the steady-state best-response function are constructed by simultaneously varying current and future  $p_0$  on the right hand side. This is in contrast to fixed points of the basic point-in-time best-response function, which are constructed holding fixed  $p_{0,t+1}$ .

### 3.2.1 Uniqueness occurs at zero inflation

A zero inflation steady state involves  $p_0 = 1$ . Such a steady state exists when the normalized quantity of money is  $m^* \equiv (\frac{\varepsilon}{\varepsilon-1}\chi)^{-1}$ . In this case, the weight on the future is  $\theta = \beta/(1 + \beta)$ , which is roughly one-half. The zero-inflation steady state is asymptotically optimal under full commitment in this model (see King and Wolman [1999]) and provides an important benchmark. Furthermore, if  $m = m^*$ , zero inflation is the *unique* steady state; that is,  $p_0 = 1$  is the unique solution to (20) when  $m = m^*$ .

### 3.2.2 Multiplicity or nonexistence must occur with positive inflation

We refer to any  $m > m^*$  as an inflationary monetary policy, because if inflation is positive in a steady state, then  $m > m^*$ , as we now show. From (20), given that  $\pi = p_0$  in steady state, we have

$$m = \frac{1}{(\frac{\varepsilon}{\varepsilon-1}\chi)} \frac{\pi}{[1 - \theta + \theta\pi]} = \frac{1}{[\theta + (1 - \theta)(\frac{1}{\pi})]} m^*.$$

Thus,  $\pi > 1$  if and only if  $m > m^*$ .

Proposition 1 states that under an arbitrary inflationary monetary policy, for low values of  $m$  there are two steady-state equilibrium values of  $p_0$ . For high values of  $m$ , no steady-state equilibrium exists. In a knife edge case there is a unique steady-state equilibrium.

**Proposition 1** *There exists an  $\tilde{m} > m^*$  such that for  $m \in (m^*, \tilde{m})$  there are two steady-state equilibria, and for  $m > \tilde{m}$  there is no steady-state equilibrium.*

**Proof.** see Appendix. ■

From (20), steady-state equilibria for a given  $m$  are fixed points of  $r(p_0; m)$ , where we write the best-response function as

$$r(p_0, m) = \frac{m}{m^*} \cdot [(1 - \theta(p_0)) + \theta(p_0) \cdot p_0] \quad (22)$$

for the discussion of proposition 1.

Figure 1 provides the basis for a heuristic discussion of Proposition 1, based on the best-response function  $r()$ . The dashed line in Figure 1 is the  $45^\circ$  line; when  $r()$  crosses this line the action of a representative adjusting firm (the horizontal axis) coincides with the optimal action of an individual firm as described by  $r()$ . The solid line is  $r()$  for  $m > m^*$ . When  $m = m^*$  it is easy to see from (22) that there is one steady state, and it occurs at  $p_0 = 1$ . An increase in  $m$  shifts  $r()$  upwards. It is thus clear that  $p_0 = 1$  is not an equilibrium point with  $m > m^*$ , but that there is a prospect for an intersection point somewhere to the right as in the case illustrated in Figure 1. At any such “low” stationary equilibrium, it must be the case that the slope is less than one (if  $r(p_0, \cdot)$  crosses the  $45^\circ$  line) or the slope is exactly equal to one (if it is a tangency). Let us call this first equilibrium  $\underline{p}_0$ .

Suppose the slope at a “low” stationary equilibrium is less than one, so that it is not a tangency and corresponds to the case illustrated in Figure 1. As  $p_0$  becomes arbitrarily large,  $\theta \rightarrow 1$ . For large  $p_0$ , then, it follows that  $r(p_0, \cdot)$  approaches the line  $(m/m^*)p_0$  from below. For high enough  $p_0$  then,  $r(p_0, \cdot) > p_0$  since we are considering an inflationary monetary policy ( $m > m^*$ ). We have assumed there was a fixed point at which  $\partial r / \partial p_0 < 1$ , and we have shown that  $r()$  lies above the  $45^\circ$  line for high enough  $p_0$ , so there must be some other “high”  $p_0$  for which there is an equilibrium  $r(\overline{p}_0) = \overline{p}_0$ . If  $m$  is high enough, the first fixed point does not exist, and  $r()$  lies everywhere above the  $45^\circ$  line. We label the two equilibria with an asterisk (\*) and carry them over to our discussion below.

There are two mechanisms at work to produce multiple steady-state rates of inflation for arbitrary constant, homogeneous monetary policy. The first is that monetary policy is accommodative: if higher prices are set by other firms today, the future nominal money stock will be higher in proportion. The second is that if all other firms raise prices today and in the future, then the future inflation rate will rise and a single firm today places higher weight on future nominal marginal costs, so that future monetary endogeneity becomes more influential on current price-setting. Looking ahead, the discretionary equilibria we will construct below will involve constant, homogeneous monetary policy. Necessarily, then, there will be multiple steady-state equilibria under discretion. However, in order to construct those equilibria we cannot rely on the steady-state best-response function.

### 3.3 Point-in-time equilibria

Solving the monetary authority's problem under discretion means computing the point-in-time equilibria that correspond to all possible current policy actions, and then picking the best action. Before studying this topic in detail in section 4, we here begin by characterizing point-in-time equilibria for an arbitrary policy action in the current period. Point-in-time equilibrium refers to the values of  $p_{0,t}$  that solve (18) for given current and future monetary actions, and a given future price  $p_{0,t+1}$ . The mechanisms described earlier lead to the potential for multiple point-in-time equilibria. We assume that the future money supply is given by  $m_{t+1} \in (m^*, \tilde{m})$ , (i.e. steady-state equilibria do exist for the assumed value of  $m_{t+1}$  and are inflationary) and that the future relative price is consistent with one of the two steady-state equilibria that may prevail if that level of  $m_{t+1}$  is maintained forever. Under these assumptions, there are either two equilibria in the current period or equilibrium does not exist. Again, in a knife edge case equilibrium is unique.

**Proposition 2** *If  $m_{t+1} \in (m^*, \tilde{m})$  is fixed, then there exists  $\check{m}$  such that for  $m_t < \check{m}$  there are two equilibria in period  $t$ , and for  $m_t > \check{m}$  equilibrium does not exist in period  $t$ .*

**Proof.** see appendix for a sketch. ■

Point-in-time equilibria are fixed points of the best-response function for current period price-setters, which we write without time subscripts, using superscript prime to denote next period:

$$p_0 = r(p_0, m, p'_0, m') = \frac{1}{m^*} [(1 - \theta(p_0, p'_0)) m + \theta(p_0, p'_0) m' p_0] \quad (23)$$

No expectation operator appears because we are assuming, for the purposes of this section, that there is no uncertainty about future  $m$  and – more importantly – future  $p_0$ . Multiplicity of point-in-time equilibria occurs for much the same reason as multiplicity of steady states. Because the future *nominal* money supply is endogenous, the current price of other firms has an effect of more than one-for-one on a single firm's desired price if agents weight the future heavily, as they do if  $m' > m^*$  and  $p_0$  is high enough. Note that as long as the *future* money supply is inflationary, there will be multiple equilibria even for noninflationary current values of the money supply.

Figure 2 illustrates the multiplicity of point-in-time equilibria for  $m = m' > m^*$ , for two different beliefs about future  $p_0$ . As above, the dashed line is the 45° line that identifies fixed points: the two points marked with asterisks (\*) on the 45° line are

the steady states from Figure 1. The solid line is the best-response function when agents expect  $\underline{p}_0$  in the future, with certainty. The low steady state is a point-in-time equilibrium when agents expect  $\underline{p}_0$  in the future, but the high steady state is not, because in that steady state agents expect  $\bar{p}_0$  rather than  $\underline{p}_0$  in the future. In fact, the second point-in-time equilibrium must be at a higher  $p_0$ , because expectations make the future less important than in the steady-state analysis of Figure 1: a larger increase in the weight on the future is required for the second fixed point to occur. The dotted line shows the best-response function when agents expect  $\bar{p}_0$  in the future, with certainty. In this case the higher of the two steady-state equilibria survives as a point-in-time equilibrium, but the low-inflation point-in-time equilibrium is now higher than the low-inflation steady state.

From (23), note that for given  $m'$ , lower  $m$  drives down the lower price equilibrium and drives up the higher price equilibrium. Lower current  $m$  shifts the best-response function down, with lower current marginal cost reducing the firm's optimal price for any price set by other firms. The lower fixed point falls, but because the basic properties of the response function are unchanged, there is still a second fixed point, now at a higher level of  $p_0$ ; at this high level of  $p_0$ , high future marginal cost offsets the lower current marginal cost. Current monetary policy actions thus affect the two equilibria in very different ways.

Figure 2 illustrates that beliefs about both current and future equilibrium selection can affect the opportunities available to a discretionary monetary authority. Raising the current money supply shifts out the best-response function for firms, resulting in a lower high- $p_0$  equilibrium and higher low- $p_0$  equilibrium. The likelihood of each equilibrium in the present will thus alter the trade-off facing the monetary authority. Beliefs about *future* equilibrium selection shift the current period best-response function for a given current money supply, and thus also alter the trade-off facing the current monetary authority.

## 4 Discretion under perfect foresight

In a perfect foresight discretionary equilibrium, the current monetary authority sets the money stock to maximize the representative private agent's welfare, subject to

1. The behavior of the future monetary authority ( $m'$ ).
2. The behavior of firms in the future ( $p'_0$ ).

3. Optimal pricing by firms in the current period ( $p_0$ ). The monetary authority must have beliefs about the selection rule used to determine  $p_0$  when a contemplated value of  $m$  leads to multiple equilibrium values of  $p_0$ .

Two conditions define a stationary perfect foresight equilibrium with discretion: (i) the current and future monetary authority each choose the same action; and (ii) the selection rule specifies that only one equilibrium will prevail in every period. It is common knowledge which equilibrium will prevail.

As we noted above, it is the essence of discretion in monetary policy that certain predetermined nominal variables are taken as given by the monetary authority. Here, the current money supply is set proportionally to the previously set price,  $P_{1,t} = P_{0,t-1}$ . This leads us to view  $m$  as the monetary authority's choice variable. Our analysis of equilibrium under arbitrary choice of  $m$  revealed that in general there were either two point-in-time equilibria or no point-in-time equilibria, as long as future policy was expected to be inflationary. This leads us to expect multiple discretionary equilibria. In this section we analyze discretionary equilibria where there is a constant probability of 1.0 on one of the two private sector equilibria.

#### 4.1 Constructing Discretionary Equilibria

We look for a stationary, discretionary equilibrium, which is a value of  $m$  that maximizes  $u(c, l)$  subject to the constraints above when  $m' = m$ . We have used two computational approaches to find this fixed point. A comparison of the two approaches is revealing about the nature of the multiple equilibria we encounter.

The first computational method involves iterating on steady states. We assume that all future monetary authorities follow some fixed rule  $m'$ . Next, we determine the steady state that prevails including the value of  $p'_0$ . Then, we confront the current monetary policy authority with these beliefs and ask her to optimize, given the constraints including the selection rule. If she chooses an  $m$  such that  $|m - m'|$  is sufficiently small, then we have an approximate fixed point. If not, then we adjust the future monetary policy rule in the direction of her choice and go through the process again until we have achieved an approximate fixed point. This approach conceptually matches our discussion throughout the text, but leaves open an important economic question: are the equilibria that we construct critically dependent on the infinite horizon nature of the problem?

The second computational method involves backward induction on finite horizon

economies. We begin with a last period, in which firms are not forward-looking in their price setting and deduce that there is a single equilibrium, including an optimal action for the monetary authority  $m_T > m^*$  and a unique equilibrium relative price  $p_{0,T}$ . Then, we step back one period, taking as given the future monetary action and the future relative price. We find that there are two private sector equilibria. In fact, this is inevitable, because the first step backwards creates a version of our point-in-time analysis above. Consequently, this approach establishes that the phenomena are associated with forward-looking pricing and homogenous monetary policy, rather than with an infinite horizon. To construct stationary nonstochastic equilibria using this approach, we can iterate backwards from the last period, computing the optimal policy,  $\{m_T, m_{T-1}, \dots\}$  and stop the process when  $|m_{t+1} - m_t|$  is small, taking  $m_t = m$  as an approximate fixed point.

In either computational approach, our work begins from the perspective that the relevant dynamic equilibrium is one that is Markovian, in the sense of Krusell and Rios-Rull [1999]. In general, this equilibrium concept restricts the actions of the policymaker to depend on a set of fundamental state variables that have intrinsic relevance to the equilibrium. In our setting, there are no such state variables, so that search for a nonstochastic Markov equilibrium corresponds to determining constant levels of public and private actions. When we do so, we find that there is more than one nonstochastic Markov equilibrium. We then consider a stochastic discretionary equilibrium in which each period's equilibrium outcome is determined by a sunspot that shifts private sector beliefs. When we consider this extension, we continue to assume that the monetary authority makes its actions a function of the state variables that are relevant to the private sector. We focus on Markov equilibria because these impose the most structure on the problem (making clear that our multiplicity arises from a single source) and provide the most tractable solution. Furthermore, the Markov equilibria of the model have natural analogues in a finite-horizon version of the model, making it clear that our results do not depend on whether the model is literally an infinite horizon one or simply the convenient stationary limit of a sequence of finite horizon models.

The numerical examples that we study next have the following common elements. The demand elasticity ( $\varepsilon$ ) is 10, implying a gross markup of 1.11 in a zero inflation steady state. The preference parameter ( $\chi$ ) is 0.9, and for convenience we set the time endowment to 5. Taken together with the markup, this implies that agents will work one fifth of their time ( $n = 1$ ) in a zero inflation steady state. With zero inflation,  $c = n = 1$  since there are no relative price distortions, and thus  $m^* = 1$ . Further, leisure ( $l$ ) is then



$5 - c$ . Accordingly, in a zero inflation stationary state, utility is just  $\ln(1) + 0.9 \cdot (5 - 1)$ . A first-best outcome would dictate that  $u(c, l)$  be maximized subject to  $c = (1 - l)$ . For the specified preferences, this leads to a first order condition  $\frac{1}{n} = \chi$  or an efficient level of work ( $n$ ) of 1.11. So, the increase in work from cutting the gross markup to one is 11.1%.

## 4.2 Optimistic Equilibrium

If the discretionary monetary authority knows that the low equilibrium will prevail, then its problem is to maximize

$$u(c, l) + v(\underline{p}_0'; m')$$

where  $v(\underline{p}_0'; m')$  denotes the future utility that corresponds to a steady state with  $m'$  and selection of the low- $p_0$  equilibrium with probability 1.0. The maximization is subject to

$$\begin{aligned} c &= c(m, \underline{p}_0) \\ l &= l(m, \underline{p}_0) \\ \underline{p}_0 &= r(\underline{p}_0, \underline{p}_0', m, m'), \end{aligned}$$

where  $r(\cdot)$  denotes the response function on the right hand side of (23), and the presence of  $\underline{p}_0$  instead of  $p_0$  is meant to imply that we place probability one on the low- $p_0$  fixed point of the response function. The monetary authority understands that future utility and current price determination is influenced by the actions of the future monetary authority, but has no way of influencing its behavior or the future price that will prevail. So, the monetary authority maximizes current period utility.

### 4.2.1 Exploiting initial conditions

Figure 3 provides some insight into the nature of the monetary authority's choice when it knows that the  $\underline{p}_0$  equilibrium will prevail for all time. For this figure, we assume that future monetary policy is noninflationary ( $m' = m^*$ ,  $p_0' = 1$ ). The current monetary authority optimally adopts an inflationary monetary policy (choosing  $m > m^* = 1$ ) because it can reduce the markup and stimulate consumption toward the first-best level. It does not completely drive the gross markup to one because an increase in  $m$  produces relative price distortions. While the relative price distortions are negligible near the noninflationary steady state, they increase convexly as monetary policy stimulates the economy. Figure 3 illustrates the sense in which New Keynesian models capture the

incentive for stimulating the economy at zero inflation, as described in Kydland and Prescott [1977] and Barro and Gordon [1983].

#### 4.2.2 An inflation bias equilibrium

Figure 4 displays the consistent steady-state equilibrium, in which agents correctly forecast the incentives of the monetary authority. Panel A shows the policymaker’s objective function, which can be thought of as an indirect utility function: the relevant portion for the current discussion is the solid line, which reaches a maximum at the value of  $m/m^* = 1.01$ . This implies a stationary relative price ( $p_0$ ) of 1.022, which is determined along the lines of Figure 2 with agents expecting  $p'_0 = p_0$  and  $m' = m$ . Given that there is a steady state,  $\pi = p_0$  and this relative price thus implies an inflation rate of 2.2 % per quarter. At this inflation rate, the monetary authority faces sufficiently increasing marginal relative price distortions that it chooses not to further increase  $m$  in an effort to further reduce the markup. Notably, the stationary markup departs little from its value at zero inflation. Stationary consumption is 99.96% of its zero inflation value, so that the markup has changed negligibly (recall that the markup and consumption are directly related by  $\mu_t = (c_t\chi)^{-1}$  with the preference specification used here).

#### 4.3 Pessimistic Equilibrium

We next suppose that the monetary authority instead knows that the high  $p_0$  equilibrium will always prevail. Its incentives are sharply different. Looking at Figure 4, we can see these incentives in the *dashed* lines, which describe a *non-equilibrium* situation in which the private sector and the monetary authority assume that the future is described by  $\underline{m}, \underline{p}_0$  while the present is described by  $\bar{p}_0$ . The monetary authority has a clear incentive to raise  $m > \bar{m}$  since this lowers the markup *and* relative price distortions, with utility being maximized when  $m$  is sufficiently high that there is exactly a tangency equilibrium in the temporary equilibrium analysis of Figure 2. Here the monetary authority “takes policy to the limit” of the set of equilibria that are imposed as its constraints. Because Figure 4 assumes optimism (that is, the low- $p_0$  outcome occurs with probability one) , there are some inconsistencies in using Figure 4 to discuss an equilibrium with pessimistic expectations. Notably, the monetary authority can lower the markup to less than one, in which case some of the firms in the economy are making losses. But the picture tells the right story: nearer the consistent discretionary equilibrium that is described by a level

$\bar{m}$ , the monetary authority still has the same incentives to raise  $m$ , but it does so without producing the curious behavior of the markup shown here.

In fact, it is not necessary to make a complicated set of fixed point computations in this case. A tangency equilibrium is one in which  $\frac{\partial r(p_{0,t}, m_t, p_{0,t+1}, m_{t+1})}{\partial p_{0,t}} = 1$ . Therefore, we can simply solve the stationary version of the equation,

$$p_{0,t} \frac{\partial r(p_{0,t}, m_t, p_{0,t+1}, m_{t+1})}{\partial p_{0,t}} = r(p_{0,t}, m_t, p_{0,t+1}, m_{t+1}),$$

to calculate the equilibrium value of  $p_0$  (this is one equation in one unknown  $p_0$  because the  $m = m'$  drops out). We can then determine the relevant  $m$  from the equation  $p_0 = r(p_0, p_0, m, m)$ .

In our numerical example, there is a consistent equilibrium with  $p_0 = 1.17$ , so that there is a 17% quarterly inflation rate in the pessimistic equilibrium with optimal discretionary policy. The associated value of  $m/m^*$  is 1.0295. This value is larger than the one used to construct Figure 3, as it should be: a higher level of  $m$  is necessary to produce a tangency equilibrium in the pessimistic case.

There are thus two steady-state equilibria with discretionary optimal monetary policy in our quantitative example, one with low inflation and one with high inflation. The levels of the inflation rates are quite different: about 2 percent (per quarter) in one case and about 17 percent in the other.

## 5 Stochastic equilibria

The generic existence of two point-in-time equilibria and two steady-state equilibria for arbitrary homogeneous policy suggests that it may be possible to construct discretionary equilibria that involve stochastic fluctuations. We now provide an example of such an equilibrium. We assume that there is an i.i.d. sunspot realized each period which selects between the two private sector equilibria: in each period, the low- $p_0$  outcome occurs with probability 0.6, the high- $p_0$  outcome occurs with probability of 0.4, and this is common knowledge.<sup>9</sup>

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<sup>9</sup>Our model does not pin down the distribution of the sunspot variable. However, some restrictions on that distribution are imposed by the requirement that every firm's profits be nonnegative in each period. For example, if  $\alpha$  is 0.75 rather than 0.6, this condition is violated in the  $\bar{p}_0$  state, and no discretionary equilibrium exists. As in Ennis and Keister (forthcoming), it would be interesting to study whether adaptive learning schemes would further restrict the distribution of the sunspot variable.

In order for its maximization problem to be well-defined, the monetary authority must have beliefs about the current and future distribution over private-sector equilibria. Above, these beliefs were degenerate. Now that they are nondegenerate, the problem is slightly more complicated. Letting  $\alpha$  be the probability of the low- $p_0$  outcome, the monetary authority maximizes

$$\{\alpha u(c(m, \underline{p}_0), l(m, \underline{p}_0)) + (1 - \alpha)u(c(m, \bar{p}_0), l(m, \bar{p}_0))\} + \beta v'$$

where  $v'$  denotes the future expected utility, which again cannot be influenced by the current monetary authority. It is important to stress that the low and high  $p_0$  values are influenced by the sunspot probabilities, since they satisfy the equations

$$p_0 = \frac{1}{m^*} \left[ \left( \frac{1}{1 + \beta E \pi(p_0, p'_0)^{\varepsilon-1}} \right) m + \left( \frac{\beta p_0}{1 + \beta E \pi(p_0, p'_0)^{\varepsilon-1}} \right) E \left\{ \pi(p_0, p'_0)^{\varepsilon-1} m' \right\} \right], \quad (24)$$

where expectations are taken over the distribution of the sunspot variable. For example,

$$E \pi(p_0, p'_0)^{\varepsilon-1} = \alpha \pi(p_0, \underline{p}_0)^{\varepsilon-1} + (1 - \alpha) \pi(p_0, \bar{p}_0)^{\varepsilon-1}.$$

Because the sunspot is i.i.d., this expression holds for both the low and high current value of  $p_0$ . Note that uncertainty prevents us from writing (24) as the simple weighted average that we used with perfect foresight.

## 5.1 Constructing Discretionary Equilibria

We can again apply the two computational approaches described in the previous section to construct Nash equilibria. In implementing these, we assume that the monetary authority and the private sector share the same probability beliefs.

## 5.2 Optimal discretionary policy

The relevant trade-offs for the discretionary monetary authority are illustrated in Figure 5. In panel A, there is a light solid line between the objective function for the low- $p_0$  private-sector equilibrium (the dark solid line) and the objective function for the high- $p_0$  private sector equilibrium (the dashed line): this is the monetary authority's expected utility objective, which is a weighted average of the two other objectives. The monetary authority chooses an optimal action that is about 1.0202, which is more stimulative than

the earlier equilibrium action (1.01, shown in Figure 4) that was appropriate under extreme optimism ( $\alpha = 1$ ). But it is smaller than the equilibrium action appropriate under extreme pessimism ( $\alpha = 0$ ).

Figure 5 also highlights that the specific values taken on by  $p_0$  in the optimistic and pessimistic equilibrium are endogenously determined in our setup, by current monetary policy and the sunspot probabilities. By contrast, in the essentially static models of Albanesi, Chari and Christiano [2002], the values of endogenous variables are not affected by the probability structure of extrinsic uncertainty.

### 5.3 Effects of sunspots

Consider now the effects of a sunspot on equilibrium quantities. We take as the reference point the levels in the low- $p_0$  private-sector equilibrium, which involve a markup of about 1.11 (close to the zero inflation markup) and a normalized price that is close to one. If the economy suddenly shifts to the high- $p_0$  private sector equilibrium as a result of the sunspot, then firms become much more aggressive in their adjustments. With the nominal money stock fixed ( $M_t = mP_{1,t-1}$ ), there is a decline in real aggregate demand since the price level rises. Consumption and work effort accordingly fall. Alternatively, the average markup rises dramatically, increasing distortions in the economy, to bring about this set of results. Quantitatively, in Figure 5, the rise in the markup is from about 1.12 to about 1.17, so that there is roughly a 4.5% increase in the markup. Given that markups and consumption are (inversely) related proportionately, there is a 4.5% decline in consumption and work effort.

## 6 Relationship to existing monetary policy literature

The study of monetary policy under discretion began with the seminal papers by Kydland and Prescott [1977] and Barro and Gordon [1983], which we will refer to as KPBG. In this early literature, output is inefficiently low, but can be raised by policies that also produce unexpected inflation. There are costs of actual inflation, so that a consistent equilibrium exhibits an inflation bias. The model that captures these ideas involves a quadratic monetary authority objective and an economic model consisting of linear behavioral equations. There is a unique discretionary equilibrium in the standard model (absent reputational effects or trigger strategies).

In recent years attention has shifted to optimization based models, such as the one

here. Models very close to ours have been studied extensively, without uncovering multiplicity under discretion. We explain why below, and we contrast the multiplicity here with that found by Albanesi, Chari and Christiano [2002] in a different type of sticky price model.

## 6.1 New Keynesian Models

There is an important recent literature that works out how the standard Kydland-Prescott-Barro-Gordon (KPBG) model can be derived from a fully articulated New Keynesian framework. The key ingredients of the models in this literature are that output is inefficiently low due to monopoly distortions; the monetary authority has temporary leverage over the real economy because of staggered price setting; and the costs of actual inflation are welfare losses associated with relative price distortions. Analyses of discretionary equilibrium in New Keynesian models has been conducted within linearized versions of those models, and using a primal approach to policy (more on this below). Just as in KPBG, there is a unique discretionary equilibrium, and it is characterized by inflation bias.<sup>10</sup>

Our analysis takes the most basic fully articulated New Keynesian model, without linearizing, and shows that there are multiple equilibria.<sup>11</sup> Our model features costs of stimulative policies – which bring about actual inflation – that stem from relative price distortions across goods. It also features benefits from unexpected stimulative policies, which lower monopoly markups and raise output toward the first best level. The model is explicitly dynamic, with firms forecasting future inflation when setting nominal prices for two periods. Multiple equilibria occur because of complementarity among price-setting firms that is induced by the response of future policy to current prices.

It should be clear from figure 2 that nonlinearity is central to the multiplicity of point-in-time equilibria we describe: the best response function of a price-setting firm is

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<sup>10</sup>For a textbook treatment, see the derivation in Woodford [2002, chapter 3]. The inflation bias result under discretion within such optimizing New Keynesian models has been popularized by Clarida, Gali and Gertler [1999].

<sup>11</sup>Much of the New Keynesian literature uses the Calvo assumption of a constant probability of price adjustment. The Calvo assumption implies that a positive fraction of firms charge a price set arbitrarily far in the past. However, for many purposes this formulation has the advantage of tractability. For our purposes however the Calvo assumption is more complicated than two period staggered pricing, because it would add a real state variable to the monetary authority’s problem. As we discuss below, adding a real state variable leaves intact the fundamental mechanism generating multiplicity.

nonlinear, and without nonlinearity there could not be multiple fixed points to that best response function. Multiplicity of steady state equilibria could survive linearization, in that one could approximate linearly around either of the two steady state discretionary equilibria. Previous analyses of discretionary equilibrium in New Keynesian models have not uncovered multiple steady states because they have used a “primal approach;” instead of specifying a policymaker who chooses an instrument and must accept whatever equilibria correspond to the instrument setting, they have specified a planner who can choose allocations (thus, prices), subject to those allocations being consistent with private-sector equilibrium.

If the policymaker can commit to future actions, the distinction between planning problem and policy problem is immaterial in New Keynesian models. However, absent commitment the distinction becomes important; the planner’s formulation rules out the steady state with lower welfare. To see this, consider a planner in the current period who knows that the future will be characterized by the steady state with lower welfare (higher  $p_0$ ). It is optimal for the planner to pick allocations that correspond to a low value of  $p_0$  in the current period, and thus the low-welfare steady state is not an equilibrium to the planning problem.<sup>12</sup> In contrast, a *policymaker*—who can only choose  $m$ —must respect private agents’ beliefs. If agents are pessimistic today and in the future, then the current policymaker chooses an  $m$  such that the low-welfare steady state outcome is realized today.

Without commitment, it is also important what the policy instrument is. If the policy instrument is the nominal interest rate instead of the money supply, Dotsey and Hornstein [2004] show that there is a unique Markov equilibrium, corresponding to the low- $p_0$  steady state of our model. This “Sargent and Wallace on their head” result is somewhat misleading however: the focus on Markov equilibria rules out a continuum of equilibria that would exist for exogenous fixed nominal interest rate policies.

## 6.2 Albanesi, Chari and Christiano

Third, our paper is closely related to recent work by Albanesi, Chari and Christiano [2002]. They find multiple equilibria in an essentially static model where a portion of monopolistically competitive firms must set prices before the monetary authority’s action

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<sup>12</sup>Wolman [2001] illustrates the exact discretionary solution to the planner’s problem in this model, and Dotsey and Hornstein [2003] solve the discretionary planner’s problem of this model using an LQ approximation. In neither case does multiplicity arise.

in each period. At the same time, the structure of the model they study is quite different from ours. The stimulative policies that produce inflation in their model also raise nominal interest rates and lead to money demand distortions, either by driving a relative price wedge between the cost of buying goods on cash and credit or by increasing transactions time. A monetary authority thus faces a trade-off between the benefits of driving down the markup and these costs. In our model, instead of the costs of realized inflation being related to money demand, they involve price distortions across goods whose prices were set in different periods.<sup>13</sup>

If there are sunspots which switch the economy between equilibria, there are also important differences in the consequences that are suggested by our model from those suggested by the ACC models. In our setting, if a high inflation equilibrium occurs when agents attach low probability to such an event, then there will be a decline in output because aggregate demand will fall and the average markup will increase. By contrast, in the ACC models, a switch from low inflation to high inflation will have little effect on the average markup or output, with the main difference being the extent of money demand distortions. Since the ACC models are essentially static ones, there is also another difference: there is no feedback between the likelihood that economic agents attach to future equilibria and the levels of inflation and output at a point in time. Accordingly beliefs about the future are of no bearing for current events. In our model, beliefs about future outcomes affect the nature of the current policy problem because firms setting their price in the current period care about both current and future monetary policy.

## 7 Discretion and Multiplicity more Generally

Multiple equilibria arise under discretion in our model because of policy-induced complementarity among private agents. The complementarity involves interaction between forward-looking firms and a future policymaker who will respond to the state variable determined by those firms. We will argue here that similar types of complementarity are present more generally when policy is formulated without commitment. For generalizations of our staggered pricing model we know this to be true, and thus we speculate on some empirical implications of monetary discretion. We then describe some other

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<sup>13</sup>Dedola (2000) studies discretionary policy in a Rotemberg-style model of pricing, and finds multiple equilibria. Dedola models money demand using a cash-in-advance constraint, and like Albanesi, Chari and Christiano, the multiple equilibria are related to the money demand specification.



contexts in which discretion can lead to multiple equilibria because of policy-induced complementarity among private agents.

## 7.1 Greater Price Stickiness

Multiplicity of equilibrium under discretion is not an artifact of two-period staggered pricing. The key model element generating multiplicity is the existence of a nominal state variable (here, the nominal price set by firms that adjusted their price in the previous period). With prices set for more than two periods, such a nominal state variable would still exist, but it would be an index of those nominal prices charged in the current period but chosen in previous periods. Furthermore, there would be real state variables, namely ratios of the current period nominal prices chosen by firms in previous periods. Solving for an equilibrium under discretion is more complicated when there is a real state that constrains the monetary authority. In Khan, King and Wolman [2001], we show that multiple equilibria still arise with three-period staggered pricing. However, that analysis is conducted using backward induction on a finite horizon model, and already with a two period horizon we encounter some headaches. There are discontinuities in the monetary authority’s policy functions, which makes it computationally difficult – though not impossible – to extend the horizon beyond two periods. For this reason we chose to focus here on the model without a state variable, where we are able to characterize equilibrium with an infinite horizon.

## 7.2 Empirical implications

There are tantalizing empirical implications of the kind of model we have discussed here. First, a model with multiple steady state rates of inflation can potentially explain why monetary policymakers can be caught at a high rate of inflation, in what Chari, Christiano and Eichenbaum [1998] call an “expectations trap.” This could explain wide variation in inflation rates across countries or time periods displaying similar structural features.

Second, the effect of sunspots on economic activity that we just discussed in section 5.3 is a situation of “unexpected stagflation” arising because of shifting beliefs. Goodfriend [1993] describes post-war U.S. recessions as arising from “inflation scares”, situations in which markets suddenly come to expect higher inflation and a contraction in aggregate demand occurs. The effect that we describe above seems to capture some aspects of this perspective, but it does not involve the increases in long-term expectations of inflation reflected in market interest rates. To consider such effects, which may be important for

understanding the interaction of the U.S. central bank with the real economy during the post-war period, one could introduce persistence into the sunspot process determining equilibrium selection.

### 7.3 Discretionary policy in other contexts

Our emphasis in this paper has been on the link between lack of commitment for monetary policy and multiple equilibria. However, the nature of the mechanism by which lack of commitment leads to multiple equilibria suggests that the phenomenon is more general. Whenever private agents' forecasts of future policy affect an endogenous state variable to which future policy responds, there is the potential for policy-induced complementarity among private agents actions. Just as in our model, even without "structural" complementarity among private agents, discretionary policy can create complementarity and lead to multiple equilibria.

A slight modification of Kydland and Prescott's flood control example fits into this framework. Suppose private agents choose among two locations, one of which experiences flooding with positive probability. Agents have idiosyncratic preferences over the two locations. After agents choose locations, a government chooses whether to impose taxes and undertake costly flood control. Suppose that the government is willing to let a small number of inhabitants be flooded, but will undertake flood control if enough agents move to the flood plain. There can be multiple equilibria here of the sort that arise in our model. When a single agent believes that no others will move to the flood plain, she knows that the government will not protect her, and chooses not to locate in the flood plain. When the agent believes that many others will move to the flood plain, she knows that the government will protect her, and she chooses to live in the flood plain. Thus, there is complementarity in agents' location decisions. That complementarity is not intrinsic, but is induced by the fact that location decisions determine a state (population in the floodplain) to which the future policymaker responds. If the policymaker could commit in advance to its action, it would determine a unique equilibrium.

Another example of lack of commitment leading to multiple equilibria comes from Glomm and Ravikumar's [1995] model of public expenditure on education. In their OLG model, young agents choose how much time to devote to learning, given their expectation of the income tax rate in the next period. Individual young agents' decisions in the current period determine next period's individual and aggregate stock of human capital. In turn, next period's government chooses the optimal tax rate as a function of the aggregate

stock of human capital, in order to fund valued public education. Thus, the future tax rate effectively responds to expectations of the future tax rate. Or, equivalently, an individual agent's current decision about human capital accumulation depends on aggregate decisions because the aggregate determines the future state (capital) to which policy will respond. For certain parameterizations the policy response induces sufficiently complementarity among private agents' decisions that there are multiple equilibria. Again, with commitment the multiplicity disappears.

## 8 Summary and conclusions

We have described equilibria under discretionary monetary policy in a basic New-Keynesian model with two-period staggered price setting. The trade-off that our monetary authority faces is a familiar one. Output is inefficiently low because firms have monopoly power. This creates an incentive for the monetary authority to provide unexpected stimulus, exploiting the pre-set prices and raising output. However, when it exploits pre-set prices, the monetary authority also raises the dispersion of prices, leading to an inefficient allocation of resources. In equilibrium, the monetary authority is balancing the marginal contribution of these two effects.

While the monetary policy trade-off is familiar, the nature of equilibrium is not. Discretionary monetary policy leads to multiple equilibria. The multiplicity occurs because of complementarity in pricing behavior that is induced by the monetary authority's natural tendency to treat the level of pre-set nominal prices as a bygone. Under discretion, in each period the monetary authority moves the nominal money supply proportionately with the nominal level of pre-set prices. This feature of monetary policy means that higher prices set by firms in the current period will lead to a higher money supply (and even higher prices) in the subsequent period. Understanding this mechanism, an individual firm adjusting its price in the current period finds it optimal to raise its price in response to higher prices set by other firms. There is complementarity in pricing, and it leads to multiple equilibria.

When we consider discretionary equilibria that are driven by a sunspot variable, the equilibria involve random fluctuations between different real outcomes.<sup>14</sup> If all firms

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<sup>14</sup>The distribution of the sunspot variable shifts the equilibrium, and while we do not pin down that distribution, it is an integral part of the definition of equilibrium. Thus far, we have only considered i.i.d. sunspot variations, so as to produce the simplest possible explanation of the source and nature of multiple equilibria. In future work, we plan to extend the analysis to the implications of persistent sunspots. This

choose to raise prices by a large amount because they (rationally) believe that others are raising prices, the result is a reduction in real aggregate demand and a decline in output relative to the level that would prevail if smaller price adjustments took place. Economic volatility then, as well as high inflation, may be a cost of discretion in monetary policy.

The mechanism leading to complementarity and multiple equilibria here transcends our example of monetary policy in a staggered pricing model. Other environments which share two features have the potential to generate similar results. First, private agents must be forward-looking and their actions must be influenced by their expectations about future policy. Second, private agents' actions must determine a state variable to which future policy responds. These features seem quite widespread, suggesting that lack of commitment may be an important cause of economic instability.

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extension would allow us to take the model more seriously as a potential explanation for some of the volatility observed in actual macroeconomic time series.

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## A Appendix

### A.1 Proofs

**Proof of Proposition 1.** (i) The conditions which characterize a steady-state equilibrium are (20) and (21). Multiplying (20) by the denominator of (21) reveals that these conditions are equivalent to

$$p_0 = h(p_0), \quad (25)$$

where

$$h(p_0) = \frac{m}{m^*} + \beta \left( \frac{m}{m^*} - 1 \right) p_0^\varepsilon \quad (26)$$

Steady-state equilibria are thus fixed points of  $h()$ , and fixed points of  $h()$  are steady-state equilibria.

(ii) For  $p_0 > 0$  the function  $h()$  is strictly positive, strictly increasing, and strictly convex.

(iii) Define  $\tilde{p}_0$  implicitly as follows:

$$\tilde{p}_0 : h'(\tilde{p}_0) = 1.$$

At  $\tilde{p}_0$ ,  $h()$  is tangent to the 45° line. By differentiating  $h()$ , we find that

$$\tilde{p}_0 = \left( \beta \varepsilon \left( \frac{m}{m^*} - 1 \right) \right)^{1/(1-\varepsilon)} > 0, \quad (27)$$

and  $\tilde{p}_0$  is decreasing in  $m$ .

Convexity of  $h()$  implies that if  $h(\tilde{p}_0) > \tilde{p}_0$  then  $h()$  does not have a fixed point, and if  $h(\tilde{p}_0) < \tilde{p}_0$  then  $h()$  has two fixed points. We now need to show that for low  $m$ ,  $h(\tilde{p}_0) < \tilde{p}_0$ , and for high  $m$ ,  $h(\tilde{p}_0) > \tilde{p}_0$ . From (27) and (26),  $h(\tilde{p}_0) \leq \tilde{p}_0$  is equivalent to

$$\frac{m}{m^*} \leq (\beta \varepsilon)^{1/(1-\varepsilon)} ((\varepsilon - 1) / \varepsilon) \left( \frac{m}{m^*} - 1 \right)^{1/(1-\varepsilon)}. \quad (28)$$

It is straightforward to show from (28) that there is a unique value of  $m$ , call it  $\tilde{m}$  such that  $h(\tilde{p}_0) \leq \tilde{p}_0$  for  $m \leq \tilde{m}$ . ■

**Proof of Proposition 2.** (Sketch) From (18) and (19), point-in-time equilibrium values of  $p_0$  are solutions to

$$\left( m^* - \frac{m}{p_0} \right) = \beta \left( \frac{g(p'_0)}{g(p_0)} p_0 \right)^{\varepsilon-1} (m' - m^*), \quad (29)$$

for fixed  $m' > m^*$  and  $p'_0$ .

- (i) The left side is strictly concave and increasing; the right hand side is strictly increasing (since  $\varepsilon > 1$ ), and either strictly concave (if  $\varepsilon < 2$ ) or strictly convex (if  $\varepsilon > 2$ ).
- (ii)  $LHS \rightarrow -\infty$  as  $p_0 \rightarrow 0^+$ , and  $\lim_{p_0 \rightarrow \infty} LHS = m^*$ .
- (iii)  $RHS(0) = 0$ .  $RHS \rightarrow \infty$  as  $p_0 \rightarrow \infty$ .
- (iv) Thus, this equation has either two solutions or no solutions.
- (v) Can show there is a unique  $m$ , call it  $\check{m}$  such that  $LHS$  and  $RHS$  are tangent.
- (iv) As  $m$  increases above  $\check{m}$ , solution disappears; as  $m$  decreases below  $\check{m}$  two solutions emerge ■



Figure 1. Steady-state best-response function for  $m > m^*$

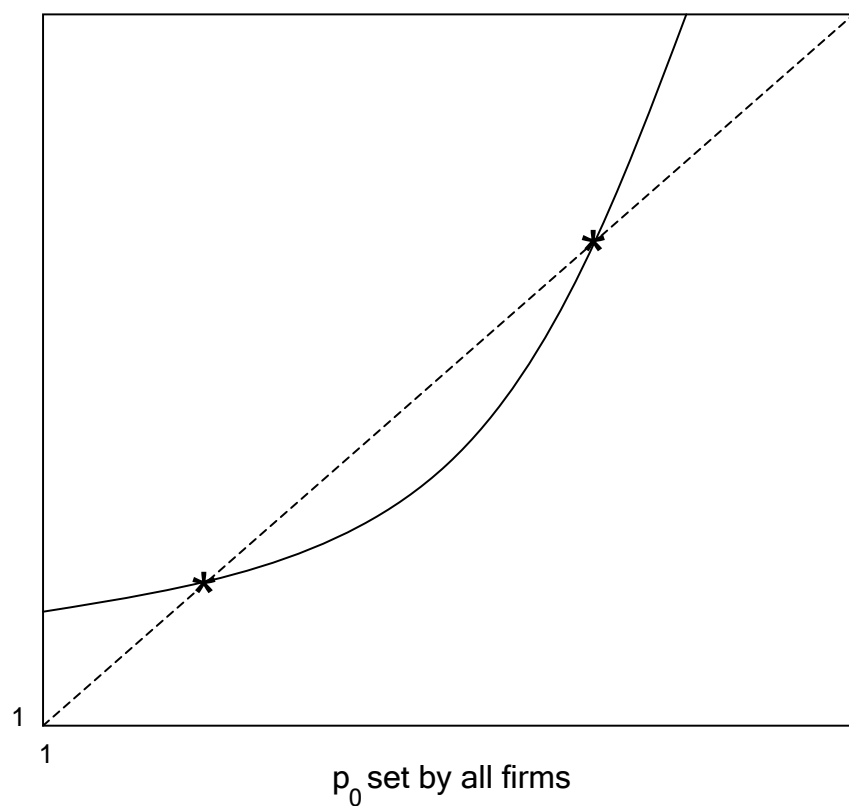


Figure 2. Point-in-time best response function for  $m=m'>m^*$

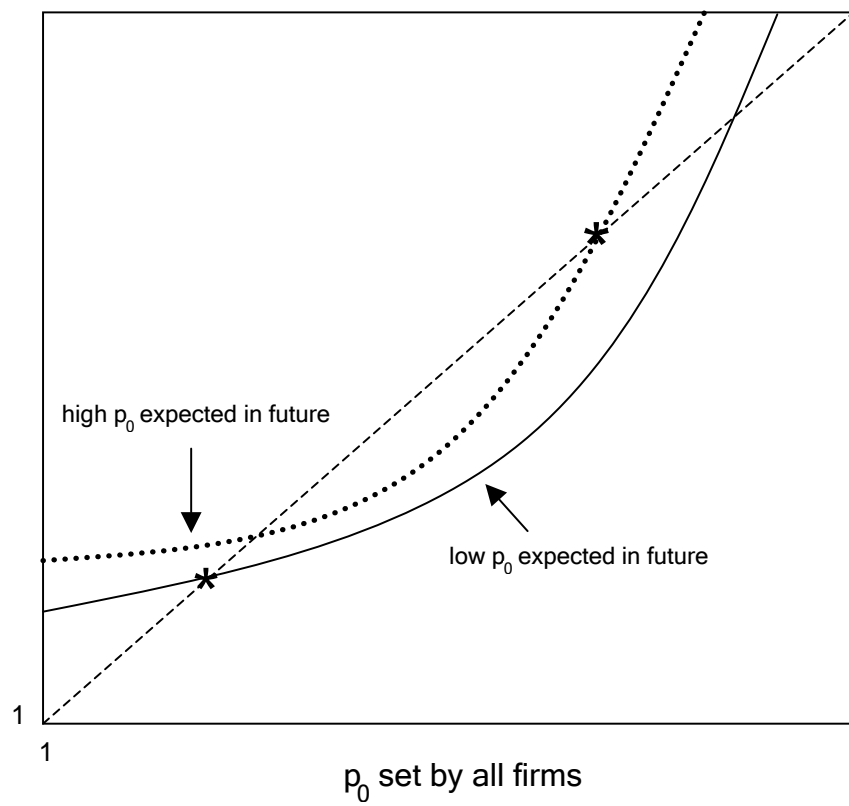
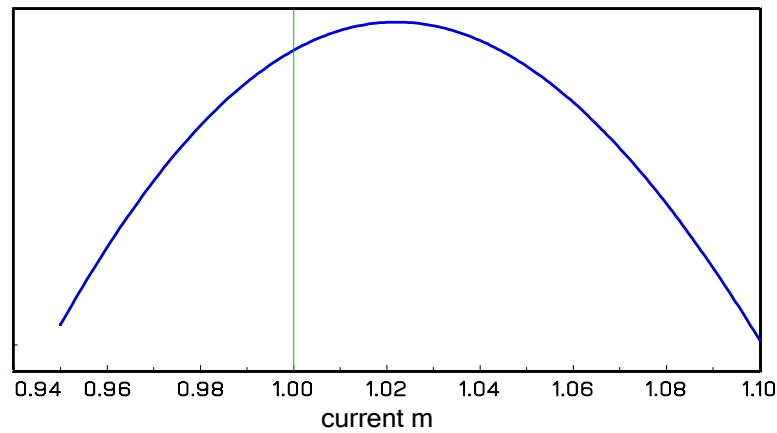
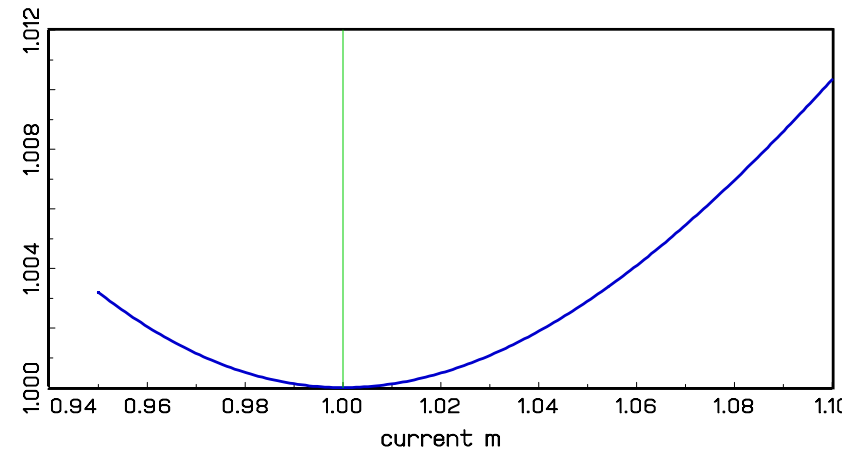


Figure 3. The temptation to stimulate a zero-inflation economy  
( $m'=1.0$ )

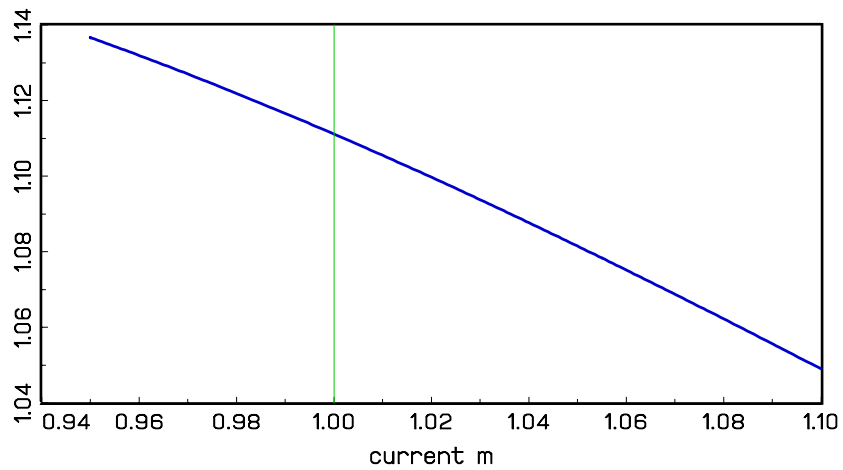
A. objective function



B. relative price distortion



C. markup



D.  $p_0$

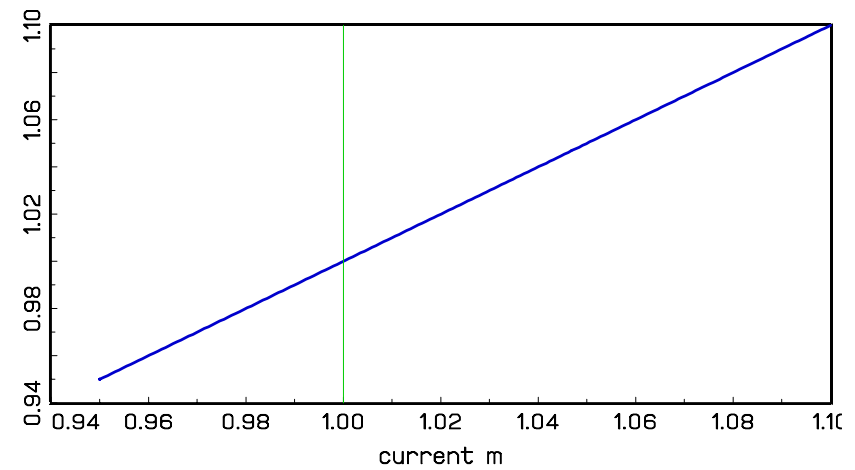
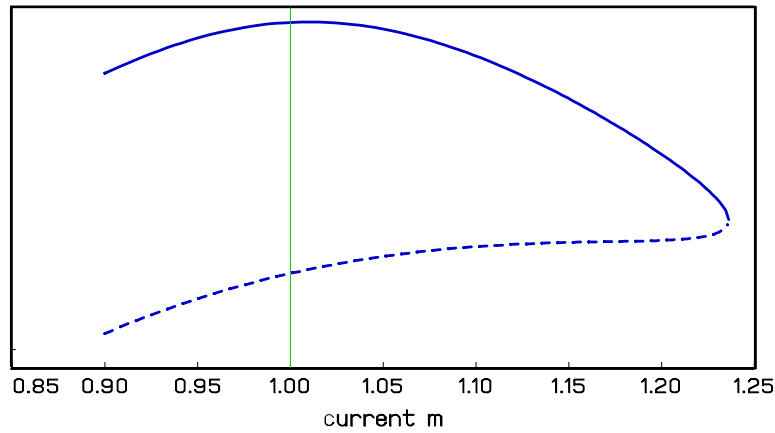
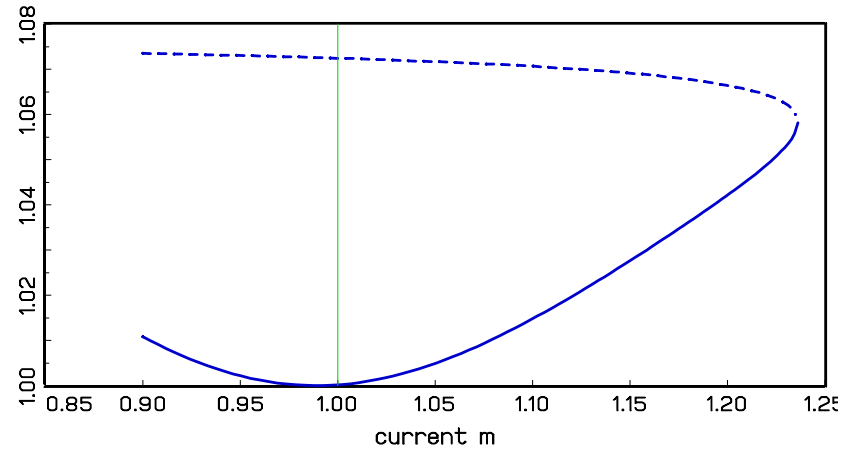


Figure 4. Discretionary equilibrium with optimism (low  $p_0$  expectations)  
Equilibrium  $m=1.010$

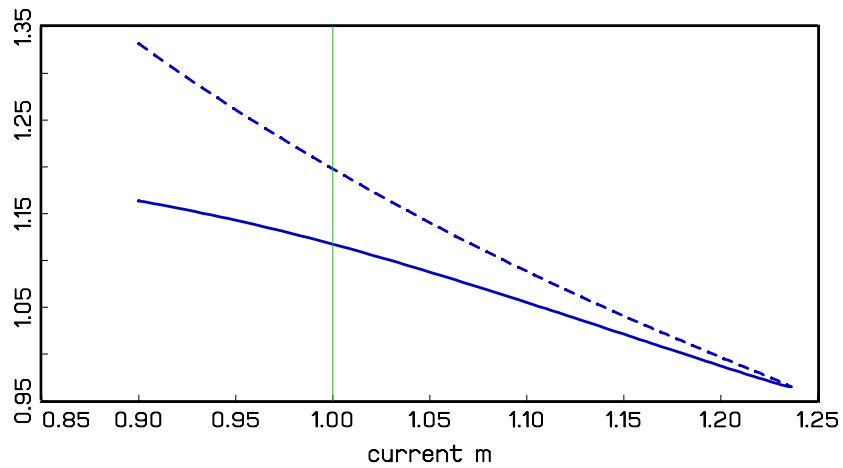
A. objective function



B. relative price distortion



C. markup



D.  $p_0$

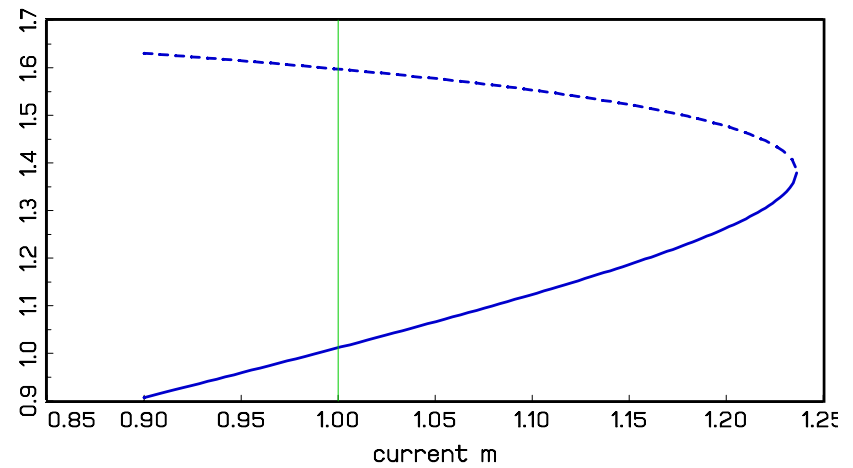
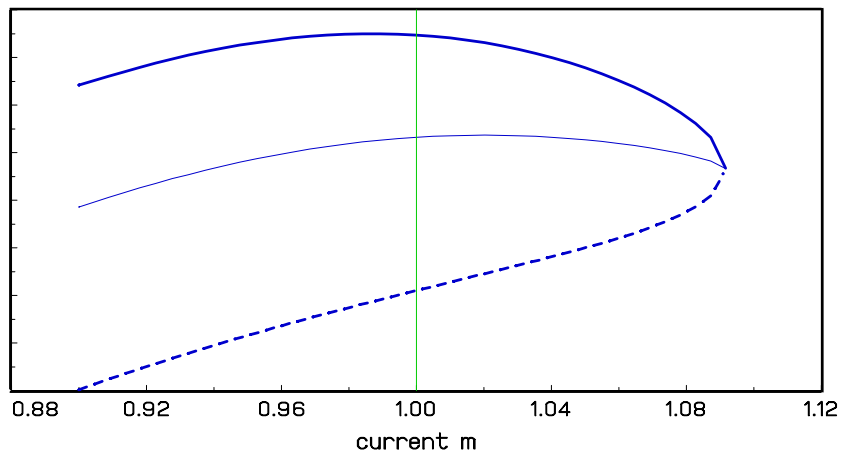
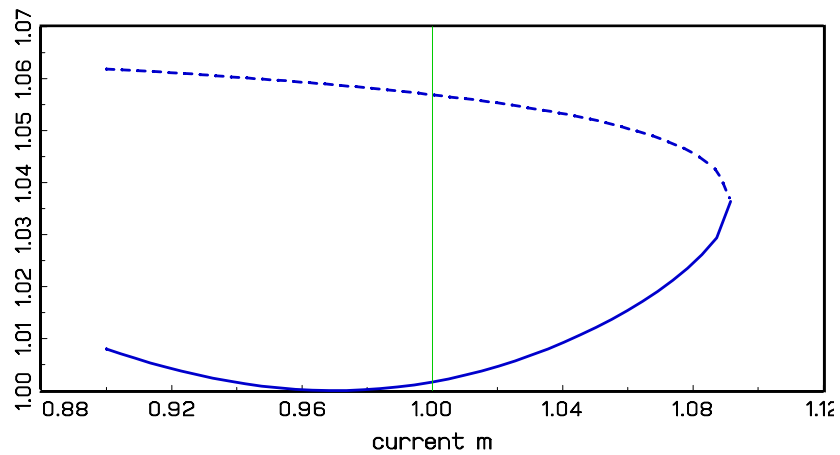


Figure 5. Discretionary equilibrium with  $\text{Prob}(\text{low } p_0)=0.6$   
Equilibrium  $m=1.020156$

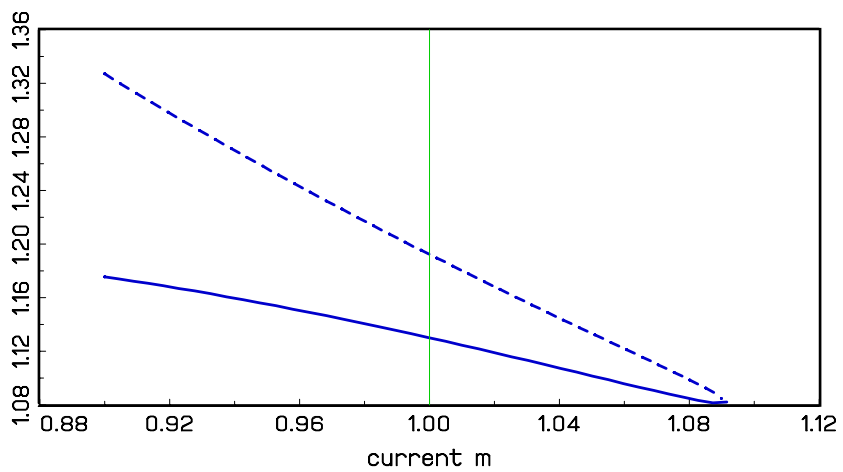
A. objective function



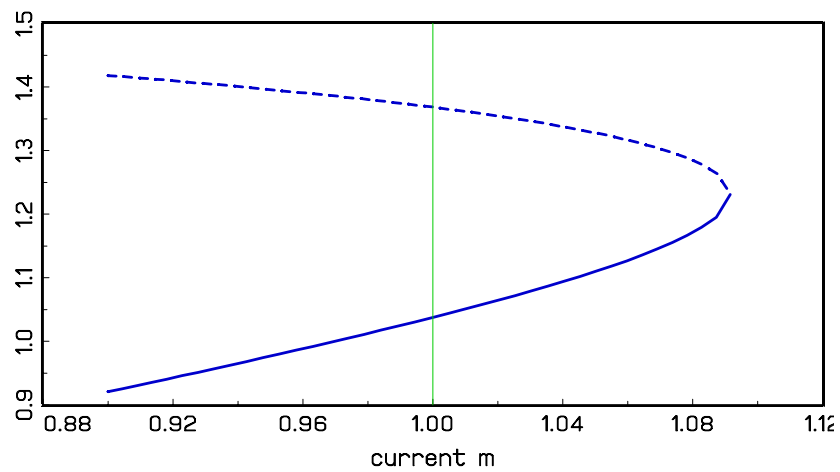
B. relative price distortion



C. markup



D.  $p_0$



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