Monetary Policy in a Stochastic Equilibrium Model with Real and Nominal Rigidities

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First draft: July 1995
This draft: March 25, 1996

Abstract

A dynamic stochastic general-equilibrium (DSGE) model with real and nominal rigidities succeeds in capturing some key nominal features of U.S. business cycles. Monetary policy is specified following the developments in the structural vector autoregression (VAR) literature. Four shocks, including both technology and monetary policy shocks, affect the economy. Interaction between real and nominal rigidities is essential to reproduce the liquidity effect of monetary policy. The model is estimated by maximum likelihood on U.S. data. The model's fit is as good as that of an unrestricted first-order VAR and that the estimated model produces reasonable impulse responses and second moments. An increase of interest rates predicts a decrease of output two to six quarters in the future. This feature of U.S. business cycles has never been captured by previous research with DSGE models. Lastly, the policy implications are discussed.

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1 Introduction

The comovement of monetary and real aggregates and the inverse relation between the movements of money growth and nominal interest rates are two prominent nominal features of business cycles in the United States and many other countries.[1] The strong and stable covariation of monetary aggregates and aggregate output has prompted several economists to focus on monetary instability as a cause of the Great Depression of the 1930s. The negative correlation of money growth and nominal interest rates is also one of the stylized facts in monetary economics. In this paper, we will try to explain these features through the two channels of monetary policy: the output effect and the liquidity effect.[2]

The output effect, defined here as the positive response of aggregate output to expansionary monetary policy, has been a key question for economists who have searched for a purely monetary explanation of the business cycle.[3] Explaining the strong relationship between money and real activity in a general equilibrium theory faces two challenges. The first is to provide a theory in which money is valued in equilibrium.[4] The second and more difficult one is to show how monetary policy has real effects in a world where economic agents are behaving rationally without simply asserting some *ad hoc* form of money illusion. In this paper, the nonneutrality of money stems from menu costs.

The liquidity effect, defined as the decrease in interest rates in response to monetary expansion, has been an important issue in empirical macroeconomics.[5] Recently, pursuing alternative assumptions for identifying monetary policy shocks, researchers provide strong empirical evidence in support of the liquidity effect. They argue that innovations in monetary aggregates reflect shocks to money demand rather than to money supply, or policy. This paper introduces this recent develop-

[1]Even if the first feature is universally accepted, the presence of the second feature is somewhat controversial. It depends on the choice of monetary aggregates and trending mechanisms. See Chari, Christiano and Eichenbaum (1995) as an example. Cooley and Hansen (1995) summarize additional stylized facts of the nominal features.

[2]In a static IS-LM framework, an increase in money supply moves interest rates down to induce larger money demand. The decrease of interest rates moves investment and output up. Interpreting the two features as the effects of monetary policy is, of course, not unanimous. Plosser (1990), following King and Plosser (1984), interprets the two features as a consequence of endogenous inside money.

[3]Friedman and Schwartz (1963) documented a strong association between periods of severe economic decline and sharp declines in the stock of money.

[4]Three frameworks have been developed: money in the utility function, transaction cost technology, and cash-in-advance constraints.

[5]This definition of the liquidity effect as a causal relation is, of course, not universal. For example, Ohanian and Stockman (1995) use the term to refer to the statistical correlation.

ment into a general equilibrium modeling.

Stimulated by Kydland and Prescott (1982) and Long and Plosser (1983), dynamic stochastic general-equilibrium (DSGE) models have become a useful tool for macroeconomic analysis, especially for business cycle analysis.[6] Previous work using a flexible-price, competitive DSGE model has provided a reasonable description of the data on real variables. Recently, the prototype DSGE models have been enriched by the introduction of non-newclassical features and sources of fluctuations other than technology shocks. Furthermore, many recent models are characterized by suboptimal equilibria, which generally provide a rationale for active government intervention.

One stream of recent work incorporates outside money in a flexible-price competitive DSGE model.[7] Money is introduced in a cash-in-advance economy by Cooley and Hansen (1989) to study the effects of inflation. Sims (1989, 1994) introduces money through a transaction-cost framework.[8] Using a simple money-in-the-utility-function model, Benassy (1995) shows analytically that the dynamics of the real variables are exactly the same as those in the model without money. Such models do not provide a good description of the money-output correlation and cannot reproduce reasonable impulse responses to the shocks in monetary policy, because of the following generic implication. If money growth displays a positive persistence, then shocks to the growth rate of money drive output down and nominal interest rate up through an anticipated inflation effect.

To generate the output effect, nominal rigidities are introduced into DSGE models.[9] There are two alternative ways of introducing nominal rigidities. The

[6]DSGE models broadly refer to real business cycle (RBC) models, equilibrium business cycle models, and neoclassical growth models. They are regarded as a paradigm for macro analysis. Prescott (1986) compares a DSGE model to the supply and demand construct of microeconomics.

[7]Despite the effort to analyze monetary phenomenon to be described below, DSGE modeling has not been used so frequently to analyze the effects of monetary policy. Friedman (1995) categorize the empirical methodologies for monetary policy into three: partial equilibrium structural models, VARs based on observed prices and quantities, and VARs based incorporating non-quantitative information. DSGE modeling is not included.

[8]The two papers focus on rather different points. Sims (1989) shows by simulation that a purely classical equilibrium model with monetary policy misses certain aspects of the actual behavior of the data. Meanwhile, Sims (1994) considers various forms of monetary policy with an emphasis on the relation with fiscal policy and discussed the existence and the uniqueness of equilibrium.

[9]Besides introducing nominal rigidities, another way to produce the output effect is to treat monetary shocks as a source of confusion that makes it difficult for agents to separate relative price changes from aggregate price changes, as in the "Lucas island model." Cooley and Hansen (1995) find that monetary shocks do not appear to play a quantitatively important role in driving business cycles in a model based on this theory. Ball, Mankiw and Romer (1988) also provides

first is to replace an equilibrium equation matching demand and supply with an equation describing the determination of price and/or wage.[10] The staggered contract theory of Fisher (1977) is usually adopted. Cho (1993), Cooley and Hansen (1995), and Cho and Cooley (1995) study the implications of nominal wage contracts for the transmission of monetary shocks, and Yun (1994) explains the comovement of inflation and output with a staggered multi-period price setting. Leeper and Sims (1994) also experiment with both price and wage rigidities by postulating equations describing price and wage movements. Another way of introducing nominal rigidities is via adjustment costs.[11] For an economic agent to have control over the price and/or wage, some form of imperfect competition is needed.[12] Following Blanchard and Kiyotaki (1987), the monopolistic competition framework has been widely used. Hairault and Portier (1993) show that monetary shocks are necessary to reproduce some stylized facts of business cycles, and Rotemberg (1994) presents a model that is consistent with a variety of facts concerning the correlation of output, prices and hours of work.[13] All the above models of nominal rigidities do indeed generate the output effect of monetary policy. However, as shown in Kimball (1995), the presence of nominal rigidities by themselves does not produce the liquidity effect. To generate the liquidity effect, I assume real rigidities in the form of adjustment costs for capital. This conjecture is found in King (1991) and implemented in King and Watson (1995) and Dow (1995).

Note that the importance attributed to the different kind of nominal rigidities has shifted over time. From Keynes until the early 1980s, nominal wage rigidities were popular in Keynesian macroeconomics. Later price rigidities gained popularity among New-Keynesians. Recently, Cho (1993) considers both types of rigidities characterized by nominal contracts and concludes that nominal wage contracts are a better way of incorporating nominal rigidities than nominal price contracts. This paper is ambivalent about the two nominal rigidities by incorporating both of them.

Meanwhile, the research on imperfect competition is partly motivated by Hall (1990) who interprets the rejection of the invariance hypothesis as the consequence of imperfect competition and/or increasing returns to scale.[14] Hornstein (1993)

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evidence against this model.

[10]However, these quantitative equations have no microfoundations in the model.

[11]Rotemberg (1987) surveys the literature on adjustment costs and Hairault and Portier (1993) incorporate price adjustment costs in a DSGE framework.

[12]In a perfectly competitive market, a firm does not set its price, but accepts the price quoted by the Walrasian auctioneer. Only under imperfect competition, when firms set prices, does it make sense to ask whether a firm adjusts its price to a shock.

[13]Rotemberg (1994) neglects the empirical behavior of interest rates and monetary aggregates, since their behavior seems to hinge on aspects of the model that are more incidental.

[14]The invariance hypothesis postulates that under perfect competition and constant returns to

and Rotemberg and Woodford (1992, 1995) discuss the consequences of introducing imperfectly competitive product markets and increasing returns into flexible-price DSGE models. Hornstein (1993) concludes that productivity shocks still account for a substantial fraction of observed output volatility. On the contrary, Rotemberg and Woodford (1992, 1995) conclude that imperfect competition changes the way in which the economy responds to various shocks and that demand shocks are important for explaining business cycles.

Outside the DSGE framework, some researchers use structural vector autoregression (VAR) models to isolate the effects of monetary policy.[15] Traditionally, the stance of monetary policy was measured by the growth rate of a monetary aggregate. This identification created a problem, called a "liquidity puzzle": monetary expansions are associated with rising rather than falling interest rates. This was documented by Melvin (1983), Reichenstein (1987) and Thornton (1988), based on single-equation distributed-lag models of interest rates. Recently, Leeper and Gordon (1992) also find that the relationship between innovations in monetary aggregates and interest rates has a sign opposite of that predicted by the liquidity effect.[16]

This problem with money-based measures of monetary policy has led Sims (1992) to identify monetary policy with innovations in interest rates. Bernanke and Blinder (1992) also argue for identifying federal funds rate innovations as policy shocks, supporting their time series analysis with institutional details. This identification scheme, while successful in producing reasonable results in some dimensions, leaves theoretical and empirical problems. For example, an expansionary monetary policy is associated with a strong and persistent drop in the price level.

Recently, Gordon and Leeper (1994), Strongin (1995) and Sims and Zha (1995) identify monetary policy in such a way that the stock of money depends on the innovations in money demand as well as in monetary policy.[17] My specification of

scale, the Solow residual is uncorrelated with all variables known neither to be causes of nor to be caused by productivity shocks. Another source of the rejection is the factor hoarding, as in Burnside and Eichenbaum (1994). Meanwhile, Evans (1992) shows that the Solow residual is Granger-caused by nominal variables such as money and interest rates using U.S. quarterly data.

[15]Compared with DSGE models which put strong restrictions on the data through optimizing behavior, structural VAR models are weakly identified time series models. They are also called identified VAR models.

[16]Traditional specification of monetary policy created another problem. While monetary aggregates Granger-cause output in a VAR without interest rates, monetary aggregates no longer Granger-cause output in the specifications with interest rates. Sims (1980) shows that interest rate innovations absorb most of the predictive power of money for output when they are included in the multivariate system.

[17]Cochrane (1994) and Pagan and Robertson (1995) survey this recent literature.

monetary policy hinges on this type of identification, by including both monetary aggregates and interest rates in the policy rule.[18] The empirical results of this paper show that this specification is important in explaining the nominal features of business cycles.

In this paper, I propose a DSGE model extended to allow for real and nominal rigidities. The model features the two effects of monetary policy.[19] It also captures many interesting U.S. business cycle facts. Section 2 presents the model and the solution. Households maximize their utility and firms maximize their profit. Government action is characterized by monetary and fiscal policies. Four shocks, including both technology and monetary policy shocks, affect the economy. The equations describing the equilibrium are log-linearized and the solution is achieved following Sims (1995).

Section 3 illustrates the model's qualitative and quantitative properties. Impulse responses from various versions of the model are provided as a way to understand the roles of various rigidities. Because the time-series and policy implications critically depend on the choice of the parameters, maximum likelihood estimates are computed.[20] The impulse responses evaluated at the estimated parameters feature the two effects of monetary policy: the output and liquidity effects. The fit of the model is comparable to that of an unrestricted first-order VAR and the variance decompositions are similar to those in the structural VAR literature. Cyclical implications are considered by comparing the second moments of the model forecasts with those of the data. Finally, one of the challenges in King and Watson (1995) is satisfactorily met by the estimated model: an increase in interest rates in the current period predicts a decrease of real economic activity two to six quarters in the future. None of their three models captures this feature of the U.S. business cycle. Section 4 concludes.

[18] For details on this identification scheme, see Bernanke and Mihov (1995) and the references therein. This point will become clear when the equation of monetary policy is formulated.

[19] Christiano and Eichenbaum (1992) propose a DSGE model with an alternative transmission mechanism of monetary policy. The model generates both the output effect and the liquidity effect due to participation constraints in the financial market. Dotsey and Ireland (1995) provide a skeptical view of the model. Beaudry and Devereux (1995) also construct a model which features the two effects by assuming predetermined prices as a way of resolving indeterminacy.

[20] For the issue of estimation versus calibration, see Kydland and Prescott (1996) and Sims (1996). See Anderson, Hansen, McGrattan and Sargent (1995) on the estimation of a DSGE model by maximum likelihood. Recent empirical work has also used other estimation methods: generalized method of moments and simulated moments.

2 The Model

The economy consists of a government and three types of private agents: an aggregator, I households indexed by i, and J firms indexed by j.[21] The aggregator serves two functions in this economy. In the labor market, it transforms heterogeneous labor into a "composite labor" usable for firms' production. In the goods market, it collects different goods to make a "composite good" which households can consume and invest.[22] Its demand for an input depends on the relative price of the input. Each household has monopoly power over its own type of labor, facing the demand by the aggregator. In both capital and goods markets, it is a price-taker. It also accumulates capital and rents it to firms. Each firm has monopoly power over its own product, facing the demand by the aggregator. It acts competitively in factor markets. The government derives revenue from issuing money and debt and expends its revenue through transfers and interest payments on outstanding debt.

The assumptions on monopoly power of households (firms) in the labor (goods) market allows nominal rigidities to arise in the form of adjustment costs for wages (prices). Following the literature on menu costs, assume that it is costly for firms to adjust their output price. Similarly, wage adjustment costs on the part of households are assumed to capture wage rigidities. Meanwhile, adjustment costs for capital give rise to real rigidities.[23]

Four shocks affect the economy. In the part of the households, a preference shock is identified as a shock in money demand. The production function of the firms involves two shocks: a technology shock and a fixed-cost shock. The last one is a shock in monetary policy. A word on information structure: variables dated t are always known at t.

[21] I and J are held fixed in the model, at least on the balanced growth path. Trade theories emphasizing the role of increasing returns to scale and imperfect competition, Helpman (1984) and Helpman and Krugman (1985) among others, endogenize the number of differentiated goods. On the consumption side, households have utility functions which reward product diversity. Rotemberg and Woodford (1995) also set up a model where the steady-state number of differentiated goods grows at the same rate as real variables, while the output of each firm is held constant. In my model, the output of each firm increases at the same rate as real variables.

[22] Because of the heterogeneity of inputs, households and firms act in a monopolistic-competition environment. Oligopolistic pricing of households and firms produces similar behavior, but the issue of collusion and punishment should be considered, as in Rotemberg and Woodford (1992).

[23] The labor market could be another source of real rigidities via efficiency wages, risk sharing contracts, or labor hoarding.

2.1 The Aggregator

Recall that there are heterogeneous households and firms. In principle, various types of labor are bought by firms for production and the goods they produce are bought by households, firms, and the government. To simplify the model and to make it comparable to the standard perfectly competitive model, all of these ultimate demanders are assumed to be interested in a "composite good" and a "composite labor" which are supplied by an artificial agent, called the aggregator.[24] Consumption and investment are measured in terms of the unit of the composite good. Firms' output depends on the quantity of the composite labor.

The aggregator's behavior is described as follows. The aggregator purchases differentiated inputs which are described by a N-dimensional vector, $(H_1, H_2, \cdots, H_N)$, and transforms them into H units of the composite output, where the functional form is:[25]

$$H = N^{\frac{1}{(1-\theta)}} \left(\sum_{n=1}^{N} H_n^{\frac{(\theta-1)}{\theta}} \right)^{\frac{\theta}{(\theta-1)}}. \tag{1}$$

This is a constant returns to scale (CRS) and constant elasticity of substitution (CES) production function which has been used in the literature on monopolistic competition, e.g. Dixit and Stiglitz (1977).[26] The parameter θ is the elasticity of substitution between the different inputs, possibly different for goods and labor. To guarantee the existence of an equilibrium, θ is restricted to be greater than unity. The supplier of each differentiated input sets a price for it; the collection of these prices describes a price vector conformable with the vector of inputs purchased. The profit of the aggregator is:

$$\Pi = PH - \sum_{n=1}^{N} P_n H_n, \tag{2}$$

where P is the price index and P_k is the price of kth input. The first order condition

[24] The presence of the aggregator can be avoided. In this case, every agent chooses the goods and labor index composition optimally, as in Blanchard and Kiyotaki (1987) and Hairault and Portier (1993). Since this choice is static and the same for all agents, notation is simplified when the aggregator solves the problem instead. This device for aggregation is a standard feature of general equilibrium trade models, for example Backus, Kehoe and Kydland (1994).

[25] The coefficient term, $N^{\frac{1}{(1-\theta)}}$, is for zero profit at the symmetric equilibrium with the price index defined as $P = \left(\frac{1}{N} \sum_{n=1}^{N} P_n^{1-\theta} \right)^{\frac{1}{(1-\theta)}}$. The coefficient term and the price index could be dispensed with if cost-minimizing behavior, instead of profit-maximizing behavior, were analyzed. However, there would remain the problem of who occupies the profit.

[26] The following results could be obtained without the global assumptions of the CES production function. See Rotemberg and Woodford (1995) for details.

with respect to H_k reduces to a constant-elasticity inverse demand function:[27]

$$P_n = P\left(\frac{NH_n}{H}\right)^{-\frac{1}{\theta}}. \tag{3}$$

In the case of labor market where the elasticity of substitution is θ_L, (3) is interpreted as follows:

$$W_{it} = W_t\left(\frac{IL_{it}}{L_t}\right)^{-\frac{1}{\theta_L}}, \tag{4}$$

where W_{it} is the wage of household i, W_t is the wage index, L_{it} is the labor supply of household i, and L_t is the amount of the composite labor supplied by the aggregator, all at time t. Note that this is a relation between the relative price and the relative quantity. Likewise, in the goods market where the elasticity of substitution is θ_Y, (3) is written as follows:

$$P_{jt} = P_t\left(\frac{JY_{jt}}{Y_t}\right)^{-\frac{1}{\theta_Y}}, \tag{5}$$

where P_{jt} is the output price of firm j, P_t is the price index, Y_{jt} is the output supply of firm j, and Y_t is the amount of the composite good supplied by the aggregator, all at time t. In the following, I use the same symbols for every agent to avoid the need for separate equations specifying market clearing conditions of the equilibrium.

2.2 Households

Households are identical, except for the heterogeneity of labor. Having monopoly power over one unit of its own labor, each household enters at time t with predetermined capital stock, money holdings and bond holdings. The household receives its rental income, its wage income, a lump-sum transfer, and a constant share of profits. It also pays the costs of adjusting its capital and wage. One source of shocks lies in the specification of preferences.

2.2.1 Preferences

Preferences are given by the utility function U_{i0} which represents the expectation of the discounted sum of instantaneous utilities, conditional on the information at time zero:

$$U_{i0} = \mathrm{E}_0\left[\sum_{t=0}^{\infty}\beta^t U\left(C_{it}, \frac{M_{it}}{P_t}, L_{it}\right)\right] \tag{6}$$

[27] Or equivalently, the demand function is $H_n = \left(\frac{H}{N}\right)\left(\frac{P_n}{P}\right)^{-\theta}$. Note that the functions have constant elasticity, which simplifies the first order conditions of households and firms.

$$= \mathrm{E}_0 \left[\sum_{t=0}^{\infty} \beta^t \frac{\left((C_{it}^*)^a (1 - L_{it})^{1-a} \right)^{1-\sigma_1}}{1 - \sigma_1} \right],$$

where

$$C_{it}^* = \left(C_{it}^{(\sigma_2 - 1)/\sigma_2} + b_t \left(\frac{M_{it}}{P_t} \right)^{(\sigma_2 - 1)/\sigma_2} \right)^{\sigma_2/(\sigma_2 - 1)}. \qquad (7)$$

The discount factor β is between 0 and 1.[28] Consumption, C_{it}, and real balances, $\frac{M_{it}}{P_t}$, interact through a CES function. The CES parameter, $\sigma_2\,(\geq 0)$, decides the elasticity of money demand. Instantaneous utility is a constant relative risk aversion (CRRA) transformation of a Cobb-Douglas function of the CES bundle, C_{it}^*, and the amount of leisure, $(1 - L_{it})$. The CRRA coefficient, σ_1, is assumed to be positive.[29] The framework of money-in-the-utility-function is adopted here. However, this model can be converted into a transaction-cost framework without altering any implications, where the variable representing consumption is not C_{it} but C_{it}^*.

The only stochastic element of households' preferences is in b_t. The variable decides the importance of consumption relative to real balances and it follows:

$$\log(b_t) = \rho_b \log(b_{t-1}) + (1 - \rho_b) \log(b) + \varepsilon_{bt}, \qquad (8)$$

where the ε_{bt}'s are i.i.d. random variables distributed $N(0, \sigma_b^2)$. Since b_t decides the level of the money demand, the innovations in b_t are identified as money demand shocks; as a matter of fact, the other shocks affect money demand only indirectly. Another element appearing in the money demand equation is σ_2, which is the elasticity of money demand. Money demand shocks could be introduced via σ_2, but it is more reasonable to introduce a randomness in the level, rather than in the elasticity. Utility maximization is subject to several constraints.

[28]For convergence of the utility function at the steady state, β need not be less than 1. Since consumption and real balances grow at a rate of $G\,(\geq 1)$, the discount factor in the stationary economy is $\beta G^{a(1-\sigma_1)}$, which is less than β, when $\sigma_1 > 1$. A sufficient condition for well-defined utility at the steady state is that $0 < \beta G^{a(1-\sigma_1)} < 1$. However, assuming that households prefer the present to the future, β lies between 0 and 1.

[29]If I assumed the additive separability of C_{it}^* and L_{it}, the only parametric class of preferences consistent with stationary labor supply would be the logarithmic utility over C_{it}^*, i.e. $\log C_{it}^* + h(L_{it})$. See the technical appendix of King, Plosser and Rebelo (1988). This corresponds to the specification of $\sigma_1 = 1$ in this model.

2.2.2 Real Rigidities via Capital Adjustment Costs

Each household accumulates capital and rents it to firms. The accumulation technology is given by the following equation:

$$K_{it} = I_{i,t-1} + (1-\delta) K_{i,t-1}, \tag{9}$$

where K_{it} is the amount of capital stock and I_{it} is the amount of investment, both at time t. The existing capital depreciates at a constant rate of δ. Note that investment is productive next period and so the capital stock is predetermined. Models of investment without adjustment costs result in too volatile investment.[30] This suggests the importance of recognizing real rigidities via adjustment costs. Adjustment costs for capital have been used to provide a rigorous foundation for the q–theory of investment. In this paper, adjustment costs are internal to the households and given by:

$$\mathrm{AC}_{it}^{K} = \frac{\phi_K}{2}\left(\frac{I_{it}}{K_{it}}\right)^2 I_{it}, \tag{10}$$

where ϕ_K is the adjustment cost scale parameter for capital. This functional form, satisfying the assumptions in Abel and Blanchard (1983), produces strictly positive steady-state adjustment costs.[31] To invest I_{it} units, the extra amount $\frac{\phi_K}{2}\left(\frac{I_{it}}{K_{it}}\right)^2 I_{it}$ is used up in transforming goods to capital. These costs are interpreted as forgone resources within households. The presence of adjustment costs makes current investment depend on the future through expectations.

Adjustment costs for capital play an important role in determining nominal and real interest rates. More investment makes installed capital more valuable due to adjustment costs.[32] However, the price of capital is expected to return to the steady state in the future. This expected decrease of capital price moves real interest rate down. This mechanism is crucial in generating the liquidity effect. Expansionary monetary policy increases investment and thus decreases real interest rate. If this offsets the anticipated inflation effect, nominal interest rate goes down: the liquidity effect.

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[30] In a continuous time model of investment without adjustment costs, investment is either infinitely positive or infinitely negative, if not zero.

[31] An alternative formulation would make installation costs a function of net investment: $\mathrm{AC}_{it}^{K} = \frac{\phi_K}{2}\left(\frac{I_{it}}{K_{it}} - \delta\right)^2 I_{it}$. This formulation produces zero steady-state adjustment costs. Quadratic costs are justified on the ground that it is easier to absorb new capacity into the firm at a slow rate. Recent literature on investment considers discontinuous adjustment costs. In special cases, the optimal rule takes an (S, s) recursive form. See Bertola and Caballero (1991) and Abel and Eberly (1994). Recently, Abel, Dixit, Eberly, and Pindyck (1995) link q-theory to option pricing.

[32] The price of capital is $\left(1 + \frac{3\phi_K}{2}\left(\frac{I_{it}}{K_{it}}\right)^2\right)$ when the price of output is normalized to 1.

2.2.3 Wage Rigidities via Wage Adjustment Costs

Following Blanchard and Kiyotaki (1987), a monopolistic-competition market structure is adopted in both labor and goods markets. As the elasticity of substitution between heterogeneous labor entering the aggregating function is not infinite, each household has market power over the market for its own labor. Therefore, each household cares about its wage level relative to the aggregate wage index. The number of households is assumed to be large enough to ensure that each household has a negligible effect on aggregate variables. Households play a Nash game on the labor market, and each one chooses its wage and labor knowing its labor demand function and taking aggregate variables as given.

Now, wage rigidities are introduced through the cost of adjusting nominal wages.[33] To obtain a simple solution to the problem, these costs are assumed to be quadratic and zero at the steady state. The real total adjustment cost for household i is given by:

$$\mathrm{AC}_{it}^{W} = \frac{\phi_W}{2}\left(\frac{P_t W_{it}}{P_{t-1} W_{i,t-1}} - \mu\right)^2 W_t, \tag{11}$$

where ϕ_W is the adjustment cost scale parameter for the wage and μ is the steady-state growth rate of money.[34] The multiplicative term, W_t, makes the costs grow at the growth rate of real wage index. This real cost, AC_{it}^{W}, enters the budget constraint of the household in a similar way to adjustment costs for capital.

Wage rigidities are a source of the output effect of monetary policy. Facing the increased labor demand induced by expansionary monetary policy, households would increase wages proportionately if it were not for adjustment costs. However, households increase wages less than proportionately because the costs of adjustment are quadratic. Their supply of labor increases and so does the output. This intuition will become clear with a graph when price rigidities are introduced.

2.2.4 Budget Constraints and First Order Conditions

The budget constraint of household i is given by:

$$C_{it} + I_{it}\left(1 + \frac{\phi_K}{2}\left(\frac{I_{it}}{K_{it}}\right)^2\right) + \frac{M_{it}}{P_t} + \frac{B_{it}}{P_t} + \mathrm{AC}_{it}^{W} \tag{12}$$

[33] Adjustment costs for wages are a device to capture the imperfection in the labor market. The framework contains the elements of search process and it is as realistic as overlapping contracts theory. Regarding the question of why it is wages, not the amount of labor, which incur adjustment costs, see below when price rigidities are introduced via adjustment costs for prices.

[34] There is also a discussion of this functional form below when price rigidities are introduced. Since adjustment costs for nominal rigidities are null at the steady state, the quadratic form with one coefficient does not lose any generality.

$$= \quad W_{it}L_{it} + Z_t K_{it} + T_{it} + \frac{M_{i,t-1}}{P_t} + \frac{r_{t-1}B_{i,t-1}}{P_t} + \sum_{j=1}^{J} s_{ij}\Pi_{jt},$$

where B_{it} is government debt, Z_t is the rental rate, T_{it} is the government lump-sum transfer payment, r_t is the gross nominal interest rate, and s_{ij} is its constant share of real profits Π_{jt} of firm j.[35] Government debt earns nominal interest rate and money is not an interest bearing asset.[36] A No-Ponzi-Game condition is imposed on households' borrowing: it requires debt not to increase asymptotically faster than the interest rate. This prevents households from borrowing to the level that makes the marginal utility of consumption zero at every period.

Noting that W_{it} is a function of L_{it} according to (4), the first order conditions are:

$$0 = \frac{\partial U}{\partial C_{it}} - \Lambda_t, \tag{13}$$

$$0 = \frac{\partial U}{\partial M_{it}} + \beta \mathrm{E_t}\left[\frac{\Lambda_{t+1}}{P_{t+1}}\right] - \left(\frac{\Lambda_t}{P_t}\right), \tag{14}$$

$$0 = \frac{\partial U}{\partial L_{it}} + W_{it}\Lambda_t \left(1 - \frac{1}{e_{it}^L}\right), \tag{15}$$

$$0 = \left(Z_t + \phi_K \left(\frac{I_{it}}{K_{it}}\right)^3\right)\Lambda_t - Q_t + \beta(1-\delta)\,\mathrm{E_t}\left[Q_{t+1}\right], \tag{16}$$

$$0 = -\Lambda_t\left(1 + \frac{3\phi_K}{2}\left(\frac{I_{it}}{K_{it}}\right)^2\right) + \beta \mathrm{E_t}\left[Q_{t+1}\right], \tag{17}$$

$$0 = \beta r_t \mathrm{E_t}\left[\frac{\Lambda_{t+1}}{P_{t+1}}\right] - \left(\frac{\Lambda_t}{P_t}\right), \tag{18}$$

where e_{it}^L is the labor demand elasticity augmented with the adjustment cost.[37] Λ_t and Q_t are the Lagrangian multipliers of the budget constraint and the capital accumulation equation and so they are interpreted as marginal utility of resources (or consumption) and marginal utility of capital, respectively.[38] All other constraints

[35]Note that s_{ij} is assumed to be a constant beyond the choice of household i. This makes calculations easier. If s_{ij} were a choice variable, a first order condition with respect to s_{ij} would put a restriction between households' and firms' discount factors. In this paper, the assumption of a complete market connects the two discount factors in the equilibrium.

[36]M2 is used as the data for money. Even if M2 earns interest, it performs better than narrower monetary aggregates from the transaction perspective. Note that I incorporate the linear trends inside the model and the trends of various variables are related each other in the equilibrium.

[37]The formulæ for e_{it}^L and the derivatives are given in the Appendix.

[38]The multiplier Q_t is slightly different from the one in a standard q-theory. It relates capital (or investment) to utility, not to profit.

are eliminated via substitution.

Combining (13), (14) and (18), a standard money demand equation is derived.

$$r_t^{-1} = 1 - b_t \left(\frac{P_t C_{it}}{M_{it}} \right)^{1/\sigma_2} . \tag{19}$$

The elasticity of real money balances with respect to the net interest rate is approximately $(-\sigma_2)$. In the following, (19) replaces (14).

Optimal capital accumulation generally involves two efficiency conditions on the part of households. The first, (16), stems from the optimal intertemporal choice of capital. If rented, the marginal utility of capital (Q_t) is the sum of three terms: the discounted and depreciated marginal utility of next period's capital $(\beta(1-\delta)\,\mathrm{E_t}[Q_{t+1}])$, the marginal utility of the rental rate $(Z_t \Lambda_t)$, and the marginal utility of the gain in adjustment costs $\left(\phi_K \left(\frac{I_{it}}{K_{it}}\right)^3 \Lambda_t\right)$. Note that the accumulation of capital reduces the adjustment cost in the next period due to a larger scale. The second, (17), is an arbitrage condition between consumption and investment. It sets the relative price of capital $\left(1 + \frac{3\phi_K}{2} \left(\frac{I_{it}}{K_{it}}\right)^2\right)$ to the marginal utility of capital $(\beta \mathrm{E_t}[Q_{t+1}])$ divided by the marginal utility of consumption (Λ_t). The marginal utility of capital is the same as the discounted marginal utility of next period's capital. In a sense, (17) can be interpreted as a demand for capital that relates investment to its marginal shadow value.

Also, to a first-order approximation, the following relation holds between the nominal interest rate and the rental rate:[39]

$$r_t = \left(\frac{(1-\delta)\,\mathrm{E_t}\left[1 + \frac{3}{2}\phi_K \left(\frac{I_{t+1}}{K_{t+1}}\right)^2\right] + \mathrm{E_t}\left[Z_{t+1} + \phi_K \left(\frac{I_{t+1}}{K_{t+1}}\right)^3\right]}{\left[1 + \frac{3}{2}\phi_K \left(\frac{I_t}{K_t}\right)^2\right]} \right) \mathrm{E_t}\left[\frac{P_{t+1}}{P_t}\right]. \tag{20}$$

It is clear from this relation that the expected decrease of investment price implies a lower nominal interest rate and that real rigidities are important in generating the liquidity effect.

2.3 Firms

Firms are identical, except for the heterogeneity of outputs. Each good is produced by one firm only, and this firm takes all other output prices as given. In the market

[39] This expression is obtained by invoking certainty equivalence, i.e. $\mathrm{E}[f(Y)] = f(\mathrm{E}[Y])$, which is justified by the assumption that the variances are very small. This could be achieved by manipulating deterministic first order conditions and restoring the expectational operators. From this expression, the real interest rate is read from the formula in the big parenthesis.

for its inputs, capital and labor, these firms behave competitively. The decision on inputs results in a certain amount of output and the amount, in turn, determines the output price from the demand curve of the aggregator. The firm also pays the cost of adjusting its output price.

2.3.1 Technology

The firm j produces Y_{jt} units of net output under a common increasing-returns-to-scale technology.[40] The production function is:

$$Y_{jt} = A_t \left(K_{jt}^{\alpha} (g^t L_{jt})^{1-\alpha} \right)^{\gamma} - \Phi_t G^t, \tag{21}$$

with the restrictions that $1 \leq \gamma \leq \alpha^{-1}$, $g \geq 1$, and $G \geq 1$.[41] K_{jt} is the capital stock and L_{jt} is the quantity of composite labor. A_t and Φ_t, common to all firms, follow the stochastic processes

$$\log(A_t) = \rho_A \log(A_{t-1}) + (1-\rho_A)\log(A) + \varepsilon_{At}, \tag{22}$$
$$\log(\Phi_t) = \rho_\Phi \log(\Phi_{t-1}) + (1-\rho_\Phi)\log(\Phi) + \varepsilon_{\Phi t}, \tag{23}$$

where $A\,(>0)$ and $\Phi\,(\geq 0)$ are the steady-state values, and ε_{At} and $\varepsilon_{\Phi t}$ are both i.i.d. variables distributed $N(0, \sigma_A^2)$ and $N(0, \sigma_\Phi^2)$, respectively. Since both of these two shocks appear in the production function, ε_{At} and $\varepsilon_{\Phi t}$ are assumed to be correlated with a correlation coefficient $\rho_{A\Phi}$. Any other pair of errors in the model is assumed to be uncorrelated.

The variable Φ_t represents a "fixed cost" component.[42] It is essential to introduce fixed costs, as they have crucial implications for productivity and profitability. In each period, the amount $\Phi_t G^t$ is used up for administration purposes just to keep production going and this is independent of how much output is produced. This "fixed cost" implies increasing returns to scale. An additional source of increasing returns to scale is embodied in γ, whenever $\gamma > 1$.[43]

[40] Firms produce different products using the same technology, which is "costless product differentiation."

[41] G is the growth rate of nonstationary real variables. To guarantee the existence of a balanced growth path, $G = g^{\frac{(1-\alpha)\gamma}{1-\alpha\gamma}}$. This functional form produces a steady state path with a geometric trend, and so the data are not prefiltered for the estimation. Incorporating a trending mechanism inside a model as above, the model integrates both growth and business cycles. See Cooley and Prescott (1995) on this point.

[42] The presence of fixed cost makes it possible for the firms to earn zero profit in the long run. Hairault and Portier (1993) interpret Φ_t as profit rather than fixed cost and they do not impose a zero profit condition in the long run. A third possible interpretation of Φ_t is an additive technology shock.

[43] There are other routes of increasing returns to scale than these two. Baxter and King (1991) use a production externality to generate increasing returns to scale.

2.3.2 Price Rigidities via Price Adjustment Costs

Each firm sells its output to the aggregator in a monopolistically competitive market. Without any other assumptions, the above firm problem is essentially a static one. I now introduce price rigidities through price adjustment costs.[44] As with wage rigidities, the real adjustment cost for firm j is given by:

$$\mathrm{AC}_{jt}^{P} = \frac{\phi_P}{2}\left(\frac{P_{jt}}{P_{j,t-1}} - \frac{\mu}{G}\right)^2 Y_t, \tag{24}$$

where ϕ_P is the adjustment cost scale parameter for price and $\frac{\mu}{G}$ is the steady-state gross inflation rate.[45]

This functional form of adjustment cost does not match the original idea of menu costs exactly. Here a firm pays the cost if the increase in its output price is different from the steady-state inflation rate, while it pays costs if it changes the price at all in the menu cost literature.[46] However, my specification may be rationalized as follows. In a stable economy, the agents will adapt themselves to a stable inflation rate. Therefore, it is costly to increase the price differently from this rate because this involves costs of advertising and also because an erratic pricing causes consumer dissatisfaction.[47]

Like wage rigidities, price rigidities are a source of the output effect of monetary policy. Figure 1 presents an intuitive explanation using an economy where the steady-state inflation rate is 1.0. The ∪-shaped dashed graph is the price adjustment cost and the two ∩-shaped graphs represent gross profits excluding adjustment cost, before and after a shock. Suppose that a firm is maximizing its profit without changing its price. In the figure, the maximum is achieved when the ratio of prices is 1.0. Profit is represented by the distance AB. Suppose that a positive demand shock moves the gross profit to the right (the dotted line) so that the maximum is achieved at 1.1. If there were no adjustment costs, the firm would increase the price by 10% and would not change the quantity of output. However, because of the adjustment cost, the firm increases the price only by 5% and also increases the

[44] One may ask why it is not quantities but prices which incur adjustment costs. A possible answer is that changing prices involves information cost. The decision by a firm to change the price should be known to its consumers, whereas the decision on quantity changes is made within a firm and need not be known to the consumers. This makes the cost of changing prices larger than that of changing quantities. The same explanation holds for adjustment costs for wages.

[45] Parkin (1986) introduces lump-sum adjustment costs and considers different monetary policies to study the implications for pricing behavior.

[46] The alternative specification following the menu cost literature is $\mathrm{AC}_{jt}^{P} = \frac{\phi_P}{2}\left(\frac{P_{jt}}{P_{j,t-1}} - 1\right)^2 Y_t$.

[47] Note also that my specification produces "second-order private costs and first-order business cycles" along the stationary path. The same argument holds for adjustment costs for wages.

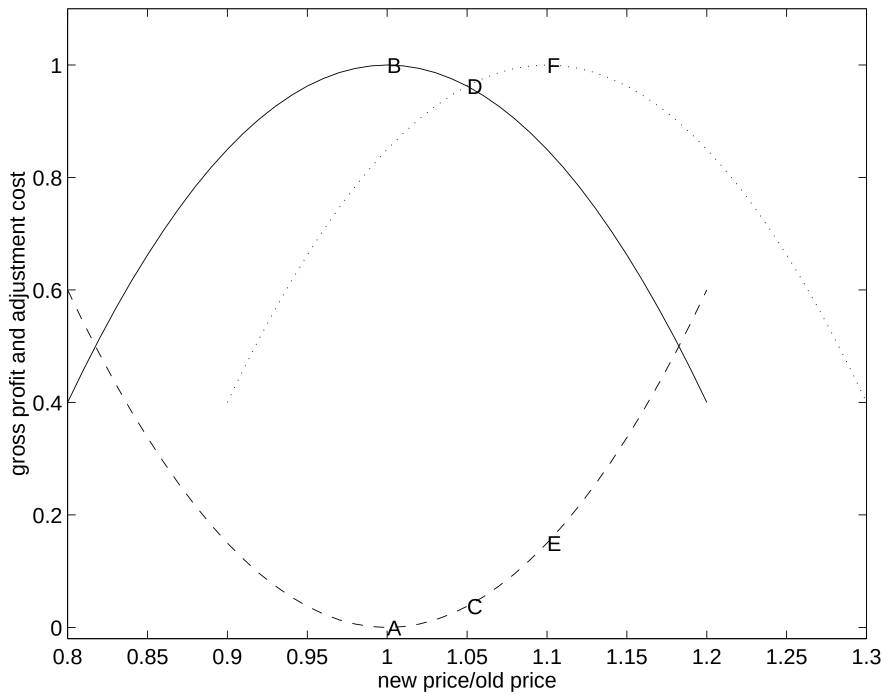

Figure 1: **Price Rigidities and the Output Effect**

quantity of output.[48] Note that CD is longer than EF in the figure. It is also clear from the figure that bigger adjustment-cost scale parameter would imply bigger output effect.

2.3.3 Value of Firms and First Order Conditions

Once price adjustment costs are introduced, the problem of firm j is dynamic: the firm maximizes its value which is the expectation of the discounted sum of its profit flows, conditional on the information at time zero:[49]

$$\Pi_{j0} = \mathrm{E}_0 \left[\sum_{t=0}^{\infty} \rho_t P_t \Pi_{jt} \right], \tag{25}$$

[48] The three graphs are quadratic with the same second derivative, which makes the firm increase the price by 5%.

[49] The problem could be divided into two parts and solved recursively. The static part is minimizing the cost subject to a given output. This part produces the conditional demand function for capital and labor. The dynamic part is maximizing the profit with capital and labor replaced by the conditional demand functions. Following this method, we could obtain the formulæ for marginal cost and markup. See Hornstein (1993) for details.

where

$$\begin{aligned}
P_t \Pi_{jt} &= P_{jt} Y_{jt} - P_t Z_t K_{jt} - P_t W_t L_{jt} - P_t \mathrm{AC}^P_{jt}, \qquad (26)\\
P_{jt} &= P_t \left(\frac{J Y_{jt}}{Y_t} \right)^{-1/\theta_Y},\\
Y_{jt} &= A_t \left(K^{\alpha}_{jt} (g^t L_{jt})^{1-\alpha} \right)^{\gamma} - \Phi_t G^t,\\
\log(A_t) &= \rho_A \log(A_{t-1}) + (1-\rho_A) \log(A) + \varepsilon_{At},\\
\log(\Phi_t) &= \rho_\Phi \log(\Phi_{t-1}) + (1-\rho_\Phi) \log(\Phi) + \varepsilon_{\Phi t},\\
\mathrm{AC}^P_{jt} &= \frac{\phi_P}{2} \left(\frac{P_{jt}}{P_{j,t-1}} - \frac{\mu}{G} \right)^2 Y_t.
\end{aligned}$$

The firm discount factor is given by a stochastic process, $\{\rho_t\}$. In the equilibrium, it represents a pricing kernel for contingent claims.

Noting that P_{jt} is a function of Y_{jt} and that Y_{jt} is a function of (K_{jt}, L_{jt}), the first order condition with respect to K_{jt} is:

$$P_t Z_t = \gamma \alpha \left(\frac{Y_{jt} + \Phi_t G^t}{K_{jt}} \right) P_{jt} \left(1 - \frac{1}{e^Y_{jt}} \right) \qquad (27)$$

where e^Y_{jt} is the output demand elasticity augmented with the adjustment cost.[50] Likewise, the first order condition with respect to L_{jt} is:

$$P_t W_t = \gamma (1-\alpha) \left(\frac{Y_{jt} + \Phi_t G^t}{L_{jt}} \right) P_{jt} \left(1 - \frac{1}{e^Y_{jt}} \right). \qquad (28)$$

Markup, the ratio of price to marginal cost, is inversely proportional to $\left(1 - \frac{1}{e^Y_{jt}}\right)$. With infinite elasticity of substitution between the different goods, the markup is constant at unity. If the elasticity is finite, it will measure the market power of the firm. With price rigidities, both technology and demand shocks affect the markup and the markup affects the real variables.[51] When a positive technology shock shifts

[50] The formula for e^Y_{jt} is given in the Appendix. If marginal cost is decreasing, the solution to (27) and (28) might not be a profit-maximizing choice. The restriction that Φ is nonnegative guarantees that the choice defined by (27) and (28) satisfies a sufficient condition for profit maximization.

[51] With flexible prices, the markup does not change with either shock. However, a technology shock affects real quantities directly, whereas a demand shock does not. When a positive technology shock occurs, the marginal cost curve shifts downward, and the firms adjust their price fully, resulting in a higher supply at a lower price according to (27) and (28). When a positive demand shock occurs, firms adjust their price to equalize marginal cost and marginal revenue, without changing the equilibrium quantity.

the marginal cost curve downward, the firm does not adjust its price fully and so the markup increases. If a positive demand shock moves marginal revenue upward, prices increase less than in the fully flexible case and output increases, which leads to a cut in the markup. Therefore, the cyclicality of the markup depends on the dominant source of shocks.

2.4 The Government

The budget constraint of the government is:

$$\left(\frac{M_t - M_{t-1}}{P_t}\right) + \left(\frac{B_t - r_{t-1}B_{t-1}}{P_t}\right) = T_t, \tag{29}$$

where

$$M_t = \sum_{i=1}^{I} M_{it}, \;\; B_t = \sum_{i=1}^{I} B_{it}, \text{ and } T_t = \sum_{i=1}^{I} T_{it}.$$

Among the five variables in the constraint, $(M_t, P_t, B_t, r_t, T_t)$, the government has two degrees of freedom since the remaining three are determined by its budget constraint and the optimizing behavior of households and firms. Government behavior is described by monetary policy and fiscal policy.

Monetary policy is specified following the developments in the structural VAR literature described and referenced in the Introduction. This literature suggests that monetary policy is best described by a combination of interest rate and monetary aggregate measures.[52] The equation can be interpreted either as one deciding money supply or as one deciding the interest rate.[53]

Interpreted in the first way, the money growth rate fluctuates around a convex combination of last period's money growth rate and the steady state money growth rate and it is also affected by a shock. Another element of monetary policy concerns the role of the interest rate. It enters the policy equation as a function of this period's interest rate, two previous periods' interest rates, and its steady state. The resulting specification constrains the government when setting its two policy variables as follows:

$$\frac{M_t}{M_{t-1}} = \left(\frac{M_{t-1}}{M_{t-2}}\right)^{\rho_M} \mu^{1-\rho_M} \left(\mu_t\right)^{1+\nu} \left(\frac{r_t r_{t-1}^{-(\rho_r+\rho_R)} r_{t-2}^{\rho_r \rho_R}}{r^{(1-\rho_r)(1-\rho_R)}}\right)^{\nu}, \tag{30}$$

[52] The Federal Reserve usually refers to money growth as an intermediate target and the nominal interest rate, the federal funds rate in practice, as an operating procedure of monetary policy. This view is repeatedly stated in various issues of the Federal Reserve Bulletin. High output growth and stable prices are referred to as the ultimate objective of monetary policy.

[53] To my knowledge of DSGE literature, a monetary policy equation includes both measures only in Sims (1989).

$$\log \mu_t \;=\; \rho_\mu \log \mu_{t-1} + \varepsilon_{\mu t}, \tag{31}$$

where r is the steady state value of r_t and the $\varepsilon_{\mu t}$'s are i.i.d. variables distributed $N(0, \sigma_\mu^2)$.

The traditional money-based measure of monetary policy corresponds to the specification of $\nu = 0$. Most DSGE research on money follows this specification. Even if my specification is richer than the traditional one, it is still limited in considering the feedback from the real side: the feedback is only through the interest rate. It would be more realistic to include the measures of real activities, income or consumption, in the monetary policy reaction function. For example, monetary policy could react to $\left(\frac{Y_t}{Y_{t-1}}\right)$ or $\left(\frac{Y_{t-1}}{Y_{t-2}}\right)$. This limitation turns out to be important in the analysis of the variance decompositions.

The parameter $\nu\,(> 0)$ embodies the sensitivity of the monetary authority to interest rate movements. The higher the parameter, the smoother the interest rate. If it is 0, the monetary authority does not care about the interest rate. If it is 1, the monetary authority increases the interest rate by 1% in response to a 1% increase of the money growth rate. If it is ∞, the interest rate becomes the only instrument of monetary policy.

The parameters, ρ_r and ρ_R, determine the targeting level of the interest rate. If both are 0, the interest rate is targeted at the steady state. If one is 0 and the other is 1, the monetary authority smooths the interest rate by targeting last period's interest rate. If both are 1, the difference of the interest rates is targeted at the difference in the last period.

The interpretation of the shock in monetary policy, $\varepsilon_{\mu t}$, is not straightforward. If we follow an extreme view of the rational expectations theory that there is a common information set in the economy, the shock should be purely random and so beyond the choice of the monetary authority. If a variable is chosen by an agent, then the variable is not random and known to every agent. However, an alternative Bayesian view allows for the difference of information sets. Having an information advantage, the monetary authority may respond to other variables that it observes but the private agents do not observe. This view does not exclude the randomness of the shock, for example an institutional randomness. In this paper, the shock represents both the randomness and the variables observed only by the monetary authority.

Note that B_{it} and T_{it} have appeared only in the households' budget constraint. Aggregating the households' budget constraints and combining it with the government budget constraint, we have B_t and T_t only in the government budget constraint.[54] This characteristic of the model is a version of Ricardian equivalence,

[54] In describing the equilibrium, I combine an aggregate version of (12) with (29).

if the subsystem without the government budget constraint and the fiscal policy exhibits a unique equilibrium. Even if Ricardian equivalence holds, fiscal policy should satisfy certain restrictions for the equilibrium to exist and be unique. Sims (1994) shows analytically which combinations of monetary and fiscal policies produce a unique equilibrium, not only locally but also globally, in a more simple model. In my model, fiscal policy is specified as follows:

$$T_t = TG^t - \tau \frac{B_{t-1}}{P_t}, \tag{32}$$

where T and τ are constant coefficients. The conditions for a unique equilibrium are checked locally and numerically.

2.5 The Equilibrium

Recall that using the same notations for every agent automatically guarantees market clearing conditions. The main part of the equilibrium is given by the optimizing behavior of the households and the firms, and the behavior of the government. However, those do not make the system complete; the number of equations is less than that of the variables by 1. It is because there has been no relation between the stochastic discount factor of the households and that of the firms.[55] To make the system complete, I assume that every agent in the economy has access to a complete and competitive market for contingent claims. That is, the firms maximize their market value. Then there is a unique market discount factor, which implies the following equation at all states:

$$\frac{\rho_{t+1}}{\rho_t} = \frac{\beta \Lambda_{t+1}}{\Lambda_t}. \tag{33}$$

We can rationalize the above equation in two different ways. First, suppose that the households, as owners of the firms, instruct the management of the firms. Then it would direct the firms to discount future profits according to its own discount factor. This is equivalent to (33). Second, as footnoted before, if an household can buy and sell the shares of the firms, then first order conditions with respect to the shares would produce (33).

There might potentially be equilibria in which identical agents behave differently. However, in view of the symmetry of the environment, it is both reasonable and practical to scrutinize a symmetric equilibrium. Note that the equations describing

[55]Note that price adjustment costs make the firm problem dynamic. Without price adjustment costs, the firm problem is reduced to a static one so there is no need to specify the firm discount factor.

the demand of the aggregator, (4) and (5), disappear since they become identities in a symmetric equilibrium. For analytic tractability, both I and J are normalized to 1.[56] Ricardian equivalence, if it holds, enables (29) and (32) to disappear from the system without affecting any variables other than B_t and T_t. Three sets of equations describing the behavior of households, firms and the government are given in the Appendix.

The variables are divided into five groups by their growth rate at the steady state. The variables that grow at a rate of G are Y_t, K_t, I_t, AC_t^P, Π_t, W_t, AC_t^W, and C_t. M_t grows at a rate of μ and P_t grows at a rate of $\frac{\mu}{G}$. The two Lagrangian multipliers, Λ_t and Q_t, grow at a rate of $G^{a(1-\sigma_1)-1}$ which is less than 1. All other variables are constant at the steady state. I use lower case letters to represent the transformed stationary variables. That is, if γ_X is the growth rate of X_t, $x_t = X_t/\gamma_X^t$. Now it is possible to transform every variable into a stationary variable.

To express the system in the transformed variables as an VAR(1) process, I define the following two new variables: the gross inflation rate and the growth rate of real wages,

$$\begin{aligned} f_t &= \frac{P_t}{P_{t-1}} = \frac{\mu p_t}{G p_{t-1}}, \\ v_t &= \frac{W_t}{W_{t-1}} = \frac{G w_t}{w_{t-1}}. \end{aligned}$$

The equations describing the problem of the households are transformed into the following equations.[57] For notational convenience, β_G replaces $\left(\beta G^{a(1-\sigma_1)-1}\right)$.

$$\begin{aligned} \mathrm{ac}_t^W &= \frac{\phi_W}{2}\left(f_t v_t - \mu\right)^2 w_t, \\ c_t &= w_t L_t + Z_t k_t + \pi_t - \mathrm{ac}_t^W - i_t\left(1 + \frac{\phi_K}{2}\left(\frac{i_t}{k_t}\right)^2\right), \\ G k_t &= i_{t-1} + (1-\delta) k_{t-1}, \\ u_t &= \frac{\left((c_t^*)^a (1-L_t)^{1-a}\right)^{1-\sigma_1}}{1-\sigma_1}, \\ c_t^* &= \left(c_t^{(\sigma_2-1)/\sigma_2} + b\left(\frac{m_t}{p_t}\right)^{(\sigma_2-1)/\sigma_2}\right)^{\sigma_2/(\sigma_2-1)}, \\ \lambda_t &= \frac{\partial u}{\partial c_t}, \end{aligned}$$

56 Consider a situation where both households and firms are distributed continuously on the real line over $(0,1)$. Integrating on the real line reduces to this normalization.

57 The formulæ for the derivatives are given in the Appendix.

$$
\begin{aligned}
r_t^{-1} &= 1 - b_t \left(\frac{p_t c_t}{m_t}\right)^{1/\sigma_2}, \\
e_t^L &= \theta_L \left[\begin{array}{c} 1 - \frac{\phi_W}{L_t}\left(f_t v_t - \mu\right)\left(f_t v_t\right) + \\ \beta_G \frac{\phi_W}{L_t} \mathrm{E_t}\left[\left(f_{t+1} v_{t+1} - \mu\right)\left(f_{t+1} v_{t+1}\right) \frac{\lambda_{t+1}}{\lambda_t}\right] \end{array} \right]^{-1}, \\
\frac{\partial u}{\partial L_t} &= -w_t \lambda_t \left(1 - \frac{1}{e_t^L}\right), \\
0 &= \left(Z_t + \phi_K \left(\frac{i_t}{k_t}\right)^3\right) \lambda_t - q_t + \beta_G (1-\delta) \mathrm{E_t}\left[q_{t+1}\right], \\
0 &= \lambda_t \left(1 + \frac{3\phi_K}{2}\left(\frac{i_t}{k_t}\right)^2\right) - \beta_G \mathrm{E_t}\left[q_{t+1}\right], \\
\lambda_t &= \beta_G r_t \mathrm{E_t}\left[\frac{\lambda_{t+1}}{f_{t+1}}\right], \\
\log\left(b_t\right) &= \rho_b \log\left(b_{t-1}\right) + (1-\rho_b) \log(b) + \varepsilon_{bt}.
\end{aligned}
$$

The equations describing the problem of the firms are transformed as follows.

$$
\begin{aligned}
y_t &= A_t \left(k_t^\alpha L_t{}^{1-\alpha}\right)^\gamma - \Phi_t, \\
\log(A_t) &= \rho_A \log(A_{t-1}) + (1-\rho_A)\log(A) + \varepsilon_{At}, \\
\log\left(\Phi_t\right) &= \rho_\Phi \log\left(\Phi_{t-1}\right) + (1-\rho_\Phi)\log(\Phi) + \varepsilon_{\Phi t}, \\
\mathrm{ac}_t^Y &= \frac{\phi_P}{2}\left(f_t - \frac{\mu}{G}\right)^2 y_t, \\
\pi_t &= y_t - Z_t k_t - w_t L_t - \mathrm{ac}_t^Y, \\
e_t^Y &= \theta_Y \left[\begin{array}{c} 1 - \phi_P \left(f_t - \frac{\mu}{G}\right) f_t + \\ \beta_G \phi_P \mathrm{E_t}\left[\frac{\lambda_{t+1}}{\lambda_t}\left(f_{t+1} - \frac{\mu}{G}\right) f_{t+1}^2\right] \end{array} \right]^{-1}, \\
Z_t k_t &= \gamma\alpha\left(y_t + \Phi_t\right)\left(1 - \frac{1}{e_t^Y}\right), \\
\alpha w_t L_t &= (1-\alpha) Z_t k_t.
\end{aligned}
$$

The equations for government behavior are transformed, too.

$$
\begin{aligned}
\frac{m_t}{m_{t-1}} &= \left(\frac{m_{t-1}}{m_{t-2}}\right)^{\rho_M} \left(\mu_t\right)^{1+\nu} \left(\frac{r_t r_{t-1}^{-(\rho_r+\rho_R)} r_{t-2}^{\rho_r \rho_R}}{r^{(1-\rho_r)(1-\rho_R)}}\right)^\nu, \\
\log(\mu_t) &= \rho_\mu \log(\mu_{t-1}) + \varepsilon_{\mu t}.
\end{aligned}
$$

Let us denote the steady state values with an upper bar. That is, $\bar{x}$ is the steady-state value of x_t. The steady state values are recursively calculated and the analytic formulæ are given in the Appendix. Two points need to be mentioned about the steady state. First, it is plausible to assume that there are zero profits in the steady state. This assumption is equivalent to determining the value of Φ as follows:

$$\Phi = \left[1 - \gamma\left(1 - \frac{1}{\theta_Y}\right)\right] A\left(\bar{k}^{\alpha}\bar{L}^{1-\alpha}\right)^{\gamma}. \tag{34}$$

The restriction that Φ is nonnegative requires that $(\theta_Y - 1)(\gamma - 1) \leq 1$. In words, if there are large increasing returns to scale (high γ), there should be a high degree of monopolistic competition in the output sector (low θ_Y). Second, $\bar{m}$ cannot be determined from the above equations, so it is treated as a parameter. In words, money is neutral in the steady state. Since the steady-state money growth rate, μ, affects the steady state through the nominal interest rate, money is not super-neutral.

Since the equilibrium cannot be solved for analytically, I log-linearize the system around the steady state. The equations describing the log-linearized model are given in the Appendix. Now the model can be cast in the form,

$$\Gamma_0\hat{x}_t = \Gamma_1\hat{x}_{t-1} + \Gamma_2\varepsilon_t + \Gamma_3\left(\hat{x}_t - \text{E}_{\text{t-1}}\left[\hat{x}_t\right]\right), \tag{35}$$

where $\hat{x}_t$ is the percentage deviation of x_t from its steady state.[58] Note that the coefficient matrices, $(\Gamma_0, \Gamma_1, \Gamma_2, \Gamma_3)$, are nonlinear functions of the deep parameters. The system is solved following Sims (1995), whose method is a generalization of Blanchard and Khan (1980). The method, based on the QZ decomposition, is analytically more general and numerically more stable.[59] The solution, if there is a unique equilibrium, takes the following form:

$$\hat{x}_t = \Psi_1\hat{x}_{t-1} + \Psi_2\varepsilon_t, \tag{36}$$

where there is no expectational term. The solution is a restricted VAR in the sense that the coefficient matrices, (Ψ_1, Ψ_2), are functions of the deep parameters. Note that the solution is equivalent to the following relation of the non-transformed variables:

$$\log(X_t) = \left[(I - \Psi_1)\log\bar{x} + \Psi_1\log\gamma_X\right] + \left[(I - \Psi_1)\log\gamma_X\right]t + \Psi_1\log(X_{t-1}) + \Psi_2\varepsilon_t,$$

where the log of a vector is the vector containing logs of the components. This relation is a first-order VAR with a constant and a time trend. The fit of the DSGE model is compared with an unrestricted VAR of this form.

[58] That is, $\hat{x}_t = \frac{x_t - \bar{x}}{\bar{x}} \simeq \log\left(\frac{x_t}{\bar{x}}\right)$.

[59] I use a modified version of the MATLAB program `gensys.m` written by Christopher Sims. The program reads $(\Gamma_0, \Gamma_1, \Gamma_2, \Gamma_3)$ from (35) as inputs and writes (Ψ_1, Ψ_2) in (36) as outputs.

Table 1: **Restrictions for Rigidities**

	$(\theta_L, \theta_Y, \gamma)$	ϕ_K	ϕ_W	ϕ_P
Prototype DSGE	$(\infty, \infty, 1)$	0	0	0
Monopolistic Comp.	free	0	0	0
Real Rigidities	$(\infty, \infty, 1)$	free	0	0
Wage Rigidities	free	0	free	0
Price Rigidities	free	0	0	free
All Rigidities	free	free	free	free

3 Effects of Monetary Policy

The structural VAR literature on the identification of monetary policy conventionally uses four variables. They are the interest rate, money stock, the price level and output: (r, M, P, Y).[60] Restricting the analysis to the above four variables preserves comparability of my model with the ones in the literature. This said, note that the data should not contain more than four variables. Since the error structure of the model comprises four shocks, using more than four variables almost always make the covariance matrix of the data to be singular: a degenerate likelihood.

3.1 Impulse Responses

Before analyzing the quantitative implications of the estimated model, it is interesting to study the impulse responses for several restricted versions. These impulse responses are drawn with respect to a 1% expansionary temporary shock in monetary policy. The qualitative role of rigidities in producing the business-cycle properties of monetary policy becomes clearer in the exercise. The parameters are set to arbitrary but plausible values and then restricted as follows.

Six specifications of the model are considered, each summarized by a row in Table 1. The first row describes a prototype DSGE model without monopolistic competition or any rigidities. The second corresponds to a model featuring monopolistic competition but no rigidities. The third introduces real rigidities alone, without monopolistic competition or nominal rigidities. Then, monopolistic competition and wage rigidities are considered in the fourth model, without real rigidities. Analogously, the fifth specification has monopolistic competition and price rigidities, without real rigidities. Finally, the full model with all parameters free has all the rigidities.

[60]These four variables lie at the heart of analysis also in King and Watson (1995).

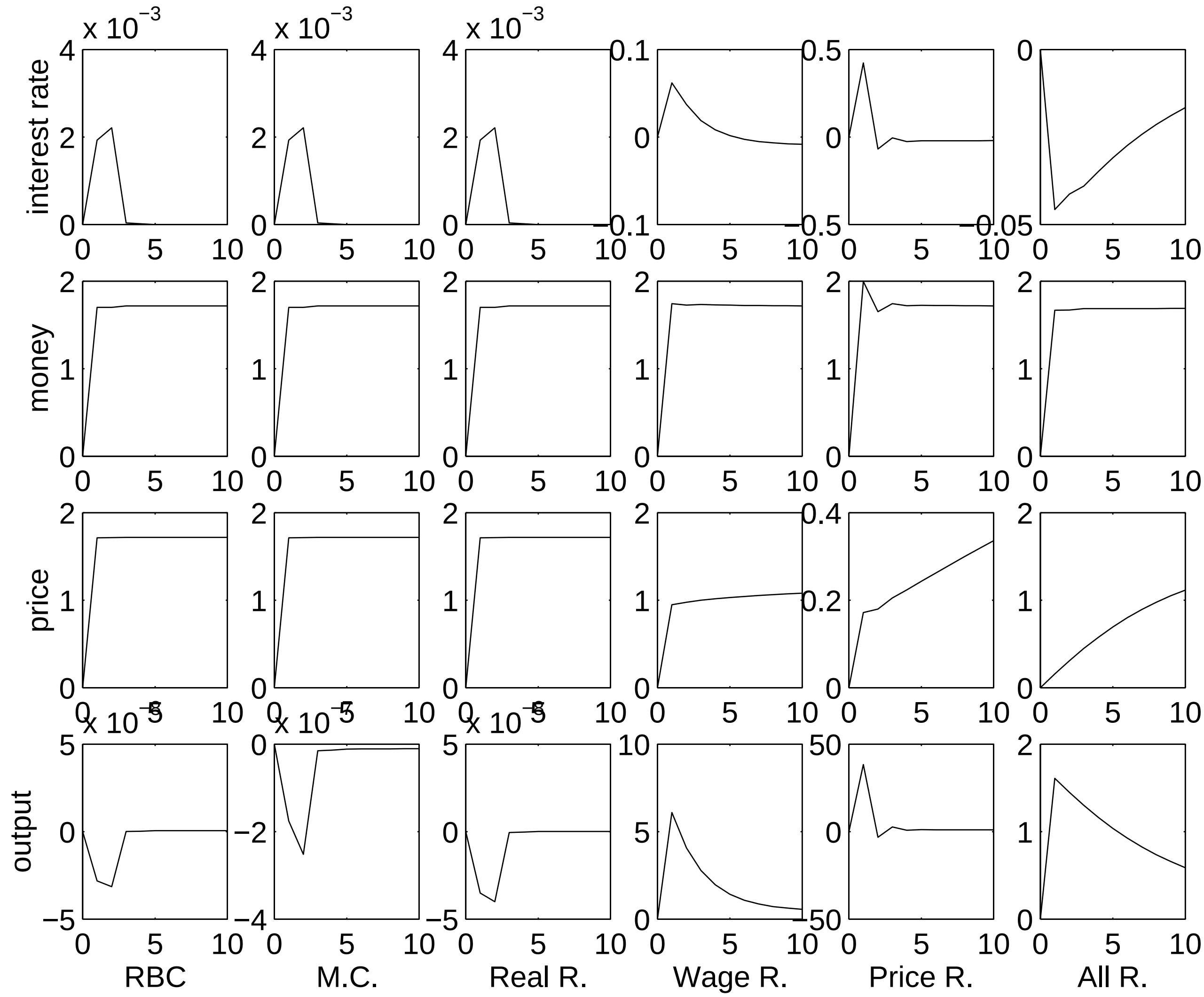

Figure 2: **Rigidities and Impulse Responses***
* The responses are with respect to a 1% expansionary shock in monetary policy.

Each column of Figure 2 corresponds to a row in the table. The first three columns illustrate how the economy responds to a monetary shock when there are no nominal rigidities. In these cases, expansionary monetary policy decreases output and increases the nominal interest rate, which is the reverse of the output effect and the liquidity effect—the two effects of monetary policy defined in the Introduction.[61]

In the first column, called `RBC` in the figure, a monetary shock has a positive effect on the interest rate and a negative effect on output. Both effects are quantitatively very small. This results from the fact that anticipated inflation, through a substitution effect, moves the interest rate up and output down.[62] The responses of the second column (`M.C.`) are similar to those of the prototype DSGE model, except for the different magnitude of the output movement. The responses in the `Real R.` column are almost the same as the prototype DSGE model, even if there are real rigidities.[63] The only difference is that the magnitude of the output movement is a little larger than that in the prototype DSGE model. Thus, real rigidities by themselves do not seem to significantly impact the behavior of the nominal variables. However, as we shall see, when real rigidities are combined with nominal rigidities, the behavior of the model responses is drastically different.[64]

The next three columns consider how the economy responds to a monetary shock when there are nominal rigidities. Nominal rigidities produce the output effect, but the liquidity effect is likely to appear only when real rigidities are added to nominal rigidities.

In the fourth column, called `Wage R.`, wage rigidities are introduced together with monopolistic competition. The impulse responses display the output effect of monetary policy. After an expansionary monetary shock, the households adjust wages only gradually due to the presence of adjustment costs. Therefore, they partially increase hours of work and this, in turn, increases output. Also note that prices do not adjust instantaneously. However, the liquidity effect does not appear. In the fifth column (`Price R.`), price rigidities replace wage rigidities. This model also exhibits the output effect of monetary policy, through the behavior of the

[61] In an IS-LM framework, an increase in money supply decreases the 'real' interest rate. However, the expectation of future inflation pushes the 'nominal' interest rate upwards.

[62] Recall the result of Benassy (1995) that the movements of real variables are not affected by nominal shocks at all. There is no room for the substitution effect since the utility function is separable among consumption, real balances, and labor.

[63] This result is robust to the size of ϕ_K, since the effect of real rigidities through the price of investment is too small compared with the anticipated inflation effect. This is not true if there are nominal rigidities.

[64] Ball and Romer (1990) also show that real rigidities, in the forms of imperfect information and efficiency wages, play a crucial role in explaining nominal rigidities and the nonneutrality of nominal shocks.

firms.[65] The firms will not adjust their price fully and would rather produce more output. The movement of prices is slower than in the model with wage rigidities. The liquidity effect does not appear, either.

A common feature of columns 4 and 5 is the significantly positive responses of the interest rate.[66] This is due to a dramatic increase in investment, not matched by an equal increase in savings. Investment increases since higher output demand in subsequent periods is expected, which then increases the rental rate.[67] Savings do not increase as much, despite the fact that there is a temporary increase in income. Furthermore, since prices adjust only gradually, expectations of future inflation also push the nominal interest rate up.[68]

The last column (`All R.`) corresponds to the full model with all the rigidities. Combining real and nominal rigidities, we finally capture the liquidity effect of monetary policy. The output effect is also quite sizable. The instantaneous increase of output is much smaller than in the models with only nominal rigidities.

3.2 Estimation Procedure

For the model to be well-defined, the parameters are restricted within the region specified in Table 2. Also, recall here a few restrictions already mentioned. The existence of a balanced growth path needs the following:

$$G = g^{\frac{(1-\alpha)\gamma}{1-\alpha\gamma}}.$$

The next restriction makes the problem of the firms well-defined:

$$1 \leq \gamma \leq \alpha^{-1},$$

[65]This model is not in accord with the argument preferring wage rigidities to price rigidities. Cho (1993) introduces nominal rigidities via nominal contracts and concludes that nominal wage contracts give a better picture of the economy. His argument is based upon the fact that the technology shock has a negative effect on output in a model with price rigidities. My model does not exhibit such an anomaly. Yun (1994) also shows that the presence of this anomaly depends on the degree of price rigidities and the specification of monetary policy.

[66]This feature is, of course, not insensitive to the parameter values. Important parameters are the serial correlation coefficients of monetary policy, ρ_M and ρ_μ. However, assigning plausible values to these parameters do not produce the liquidity effect. Note also that the positive response of the interest rate in `Price R.` induces the overshooting behavior of the money stock.

[67]This increase of the real interest rate is not a generic result of a sticky price model. In a cash-in-advance model of Ohanian and Stockman (1995), monetary expansion decreases the real interest rate.

[68]To describe this in terms of an IS-LM framework, the two expectational effects of an increase in money supply shifts out the IS curve so much that it overwhelms the more usual shift of the LM curve, to raise both real and nominal interest rates.

Table 2: **Parameter Region**

parameters	region
α, β, δ, a	$(0,1)$
$\gamma, G\,(\text{or } g)\,, \mu, \theta_L, \theta_Y$	$(1,\infty)$
$A, \phi_K, \phi_W, \phi_P, b, \bar{m}, \nu$	$(0,\infty)$
$\rho_b, \rho_A, \rho_\Phi, \rho_{A\Phi}, \rho_\mu, \rho_M, \rho_r, \rho_R$	$(-1,1)$
$\sigma_b^2, \sigma_A^2, \sigma_\Phi^2, \sigma_\mu^2, \sigma_1, \sigma_2$	$(0,\infty)$

$$1 \;\leq\; \gamma \leq \frac{\theta_Y}{\theta_Y - 1}.$$

The requirement that the model has a unique solution forces additional restrictions on the parameter space which cannot be expressed in an analytic form. For any parameter vector which produces no equilibrium or multiple equilibria, the likelihood value is set to a very small number so as not to affect the maximum of the likelihood function.[69] Therefore, the likelihood function is discontinuous on the boundary.

For a parameter vector in the region of a unique equilibrium, the solution of the log-linearized model takes the form of (36). This is used in the construction of the likelihood, which is defined as the log-likelihood conditional on the first observation, i.e.

$$\mathrm{LH}\left(\Theta; X_1, X_2, \cdots X_T\right) = \log\left(\mathrm{pdf}\left(\hat{x}_2, \hat{x}_3, \cdots \hat{x}_T | \hat{x}_1\right)\right) + \sum_{t=2}^{T} \log\left|\frac{\partial \hat{x}_t}{\partial X_t}\right|, \tag{37}$$

where Θ is a vector of all the parameters. The likelihood reported below excludes the constant term of the normal density involving π and the Jacobian term, since the same forms appear in the likelihood of a comparable VAR to the logged data.

The evaluation of the likelihood is nonstandard in two ways: the variance of the error term is not full rank and some of the variables are not observed in the data. Moreover, the dimension of the variance-covariance matrix of the full data is so large that the matrix cannot be stored on a personal computer. Therefore, we need a recursive way of computing the likelihood which avoids storing the matrix.

[69] From a Bayesian perspective, this is equivalent to putting a zero prior probability on the region of the parameter space where the model does not exhibit a unique solution. Some researchers, Farmer (1993) for example, say that a model with multiple equilibria is theoretically reasonable and empirically plausible. Kim (1994) argues that those researchers examined the plausibility of indeterminacy without presenting a formal statistical test and proposes a posterior odds ratio test, which formally tests for the existence of indeterminacy.

In this paper, the likelihood is calculated by the Kalman filtering method.[70]

The above discontinuities are problematic for usual optimization routines based on a gradient method. Optimization routines which do not require gradient evaluation can be used instead, for example Nelder-Meade. However, given the large dimension of the parameter vector to estimate, it would be inefficient to use this routine. For the estimation of the model, I use a routine which is robust to discontinuities even if it is based on a gradient method.[71]

Quarterly U.S. data from 1959:I to 1995:I are extracted from Citibase. The Appendix contains the exact data descriptions and Figure 6 plots the data for the levels, the log-levels, the percentage deviations, and the log-differences. Since the data set includes only four variables, the estimation produces large standard errors for the parameters which are not very relevant for the movement of those four variables.[72] Especially, only one out of the four variables is a real variable, so the parameters which are mainly related with real variables are loosely estimated. Also, the discussion of the estimates will be focused on the parameters most relevant to the effects of monetary policy.

3.3 Estimation Results

Let us begin with the preference parameters given in Table 3.[73] The discount factor, β, is 0.999. It is larger than the usually calibrated value, but similar to other estimation results. For example, the estimate in McGrattan, Rogerson, and Wright (1995) is 1.001. The share of consumption in utility, a, is 0.672, with a standard deviation of 0.658. Thus, my estimate is within one standard deviation of the conventionally calibrated value, 0.4. The standard deviations are given in the parentheses. The CRRA coefficient, σ_1, is 12.18 with a standard error of 7.30, therefore the hypothesis of the logarithmic preferences ($\sigma_1 = 1$) is rejected at a 10% significance level, but not at a 5% significance level. Both the elasticity of substitution between consumption

[70] An alternative method based on approximating an infinite order VAR with a finite order VAR can be used instead. Kim (1995) explains both methods and compares them from a computational perspective.

[71] The routine is implemented by a MATLAB program `csminwel.m` written by Christopher Sims.

[72] The standard errors are computed by using the second derivatives of the (log) likelihood function. The Hessian of the likelihood function is evaluated at the estimates and then inverted. The standard errors are read as the roots of the diagonal elements. Note that the justification for computing these t-statistics is Bayesian and that they should be interpreted carefully. The standard errors and test statistics computed here are meant as characterizations of the shape of the likelihood function, which under weak regularity conditions are asymptotically normal-shaped regardless of the presence of unit roots and cointegrations.

[73] The parameters for capital accumulation are explained later together with the technology parameters.

and real balances, σ_2, and the steady-state share of real balances in the consumption bundle, b, are very close to the calibrated values of Hairault and Portier (1993). The shock in money demand, b_t, is persistent, with an autoregressive coefficient 0.99, and has an unconditional variance of $0.40\left(=\frac{0.008}{1-0.99^2}\right)$.

Table 3: **Preference Parameters**

Description	Function	Parameter estimates
utility function	$\frac{\left(\left(C_i^*\right)^a (1-L_i)^{1-a}\right)^{1-\sigma_1}}{1-\sigma_1}$	$a = 0.672$, $\sigma_1 = 12.18$, (0.658) (7.30)
discount factor	$\mathrm{E}_0\left[\sum_{t=0}^{\infty} \beta^t U\left(C_t, \frac{M_t}{P_t}, L_t\right)\right]$	$\beta = 0.999$, (0.011)
C_t^*	$\left(C_t^{(\sigma_2-1)/\sigma_2} + b_t\left(\frac{M_t}{P_t}\right)^{(\sigma_2-1)/\sigma_2}\right)^{\sigma_2/(\sigma_2-1)}$	$\sigma_2 = 0.112$, $b = 6 \times 10^{-21}$, (0.060) (1×10^{-19})
money demand shock	$\log\left(\frac{b_t}{b}\right) = \rho_b \log\left(\frac{b_{t-1}}{b}\right) + \varepsilon_{bt}$	$\rho_b = 0.990$, $\sigma_b^2 = 0.008$, (0.018) (0.008)

Bayesian standard errors in parentheses.

The estimated parameters for monopolistic competition and the rigidities are in Table 4. The degree of monopolistic competition is higher in the output sector, as one may expect, and so is the rigidity coefficient. Despite that, note that one should consider also the other coefficients affecting the households' and the firms' choices in order to assess the relative importance of the two nominal rigidities. However, such an assessment is beyond the scope of this paper. The estimate for real rigidities ($\phi_K = 312$) implies that, at the steady state, the installation of 100 units of capital is accompanied by 5.6 units as the adjustment cost. The parameter is very sharply estimated with a standard error of 4.

The estimated parameters for capital accumulation and technology are in Table 5. The value of depreciation, δ, is 0.019 and so close to the conventionally calibrated value, 0.015 or 0.020. The parameter for the capital income share, α, is too small and the parameter for increasing returns, γ, is too large.[74] However, since their standard errors are large, these parameters are within one standard error of plausible values.[75]

[74] Since γ is so large, the labor-augmenting growth factor, g, is very close to 1. It is 1.0001.

[75] Pegging γ at a reasonable value, I obtained another local maximum of the likelihood function which attains the same likelihood value. At the new estimate, however, the risk-aversion parameter, σ_1, becomes too large. Again, its standard error is large. Meanwhile, the empirical results such as impulse responses and variance decompositions are not much affected by which estimate is used. That is, the model is weakly identified in these dimensions. This calls for further research using more data on real variables to obtain sharper estimates.

Table 4: **Monopolistic Competition and Rigidities**

Description	Function	Parameter estimates
monopolistic competition	$W_i = W\left(\frac{IL_i}{L}\right)^{\frac{-1}{\theta_L}}$ $P_j = P\left(\frac{JY_j}{Y}\right)^{\frac{-1}{\theta_Y}}$	$\theta_L = 12.37$, (13.38) $\theta_Y = 1.101$, (0.240)
nominal rigidities	$\mathrm{AC}_t^W = \frac{\phi_W}{2}\left(\frac{P_t W_t}{P_{t-1}W_{t-1}} - \mu\right)^2 W_t$ $\mathrm{AC}_t^P = \frac{\phi_P}{2}\left(\frac{P_t}{P_{t-1}} - \frac{\mu}{G}\right)^2 Y_t$	$\phi_W = 0.153$, (0.297) $\phi_P = 0.806$, (1.815)
real rigidities	$\mathrm{AC}_t^K = \frac{\phi_K}{2}\left(\frac{I_t}{K_t}\right)^2 I_t$	$\phi_K = 312$, (4)

Bayesian standard errors in parentheses.

The estimates of γ by Hall (1990) for U.S. manufacturing industries range from 1.1 to 10.The growth rate of output, $G\,(= 1.002)$, is smaller than the average growth rate of data on output, 1.003. This is partly because the upward movement of output may be caused by persistent shocks in the production function.

The estimated autoregressive processes for the shocks related with the production function are also reported in Table 5. The technology shock is very persistent, with an autoregressive coefficient of 0.981, and has an unconditional variance of $0.008\left(= \frac{0.0003}{1-0.981^2}\right)$, much smaller than usually calibrated values. The fixed-cost shock is also persistent, with an autoregressive coefficient of 0.911, and has an unconditional variance of $0.11\left(= \frac{0.020}{1-0.911^2}\right)$. The variance of the fixed-cost shock is larger than that of the technology shock. The two shocks are negatively correlated with a correlation coefficient of (-0.656). The fixed-cost shock is very important in the estimated model, which may indicate a problem in the conventional specification of a production function that does not include an additive term.

Lastly, the parameters for monetary policy are in Table 6. The estimate of the growth rate of money, μ, is 1.013 and this is very close to the average money growth rate of the data, 1.014. The parameter for the sensitivity of the interest rate, ν, is 0.576 and significantly different from 0. This indicates that the conventional specification of monetary policy in the DSGE literature that does not include the interest rate is not empirically supported.[76] The serial correlation of the money growth rate, ρ_M, is negative but this is offset by the positive serial correlation of

[76] Note that there are near unit roots in the interest rate process and that the model implies strong restrictions on the geometric trends of the four variables. In order to check the robustness of the estimates against the low frequency properties of the data, it is worth estimating the transformed model using filtered data to eliminate low frequencies and comparing the estimates with those of this paper.

Table 5: **Technology Parameters**

Description	Function	Parameter estimates
production function	$Y_t = A_t\left(K_t^{\alpha}(g^t L_t)^{1-\alpha}\right)^{\gamma} - \Phi_t G^t$	$\alpha = 0.225$, (0.260) $\gamma = 3.808$, (5.905) $G = 1.002$, (0.002)
capital accumulation	$K_t = I_{t-1} + (1-\delta) K_{t-1}$	$\delta = 0.019$, (0.055)
technology shock	$\log(\frac{A_t}{A}) = \rho_A \log(\frac{A_{t-1}}{A}) + \varepsilon_{At}$	$\rho_A = 0.981$, (0.025) $\sigma_A^2 = 0.0003$, (0.0002)
fixed-cost shock	$\log\left(\frac{\Phi_t}{\Phi}\right) = \rho_\Phi \log\left(\frac{\Phi_{t-1}}{\Phi}\right) + \varepsilon_{\Phi t}$	$\rho_\Phi = 0.911$, (0.029) $\sigma_\Phi^2 = 0.020$, (0.008) $\rho_{A\Phi} = -0.656$, (0.298)

Bayesian standard errors in parentheses.

the shock in monetary policy, ρ_μ. This shock is mildly serially correlated with a coefficient of 0.487 and has an unconditional variance of $0.00005\left(= \frac{0.00002}{1-0.487^2}\right)$.

Table 6: **Parameters for Monetary Policy**

Description	Function	Parameter estimates
monetary policy	$\frac{M_t}{\mu M_{t-1}} = \left(\frac{M_{t-1}}{\mu M_{t-2}}\right)^{\rho_M} (\mu_t)^{1+\nu} \times \left(\frac{r_t r_{t-1}^{-(\rho_r+\rho_R)} r_{t-2}^{\rho_r \rho_R}}{r^{(1-\rho_r)(1-\rho_R)}}\right)^{\nu}$	$\nu = 0.576$, (0.266) $\rho_M = -0.158$, (0.085) $\rho_r = 0.999$, (3.771) $\rho_R = 0.980$, (3.582)
monetary policy shock	$\log(\mu_t) = \rho_\mu \log(\mu_{t-1}) + \varepsilon_{\mu t}$	$\rho_\mu = 0.487$, (0.006) $\sigma_\mu^2 = 0.00002$, (0.00001)

Bayesian standard errors in parentheses.

The parameters describing the fiscal policy, T and τ, are not identified if the economy is a version of Ricardian equivalence. Even if Ricardian equivalence does not hold, the parameters are so weakly identified that they are not included in the estimation.

3.4 Assessing the Fit

We have seen how the log-linearized first order conditions produce the solution of which the form is a restricted first-order VAR to all the variables. Since the VAR structure allows us to interpret the likelihood as a measure of the "normalized mean squared error of forecasts," it is natural to compare the fit of the DSGE model with that of a comparable unrestricted VAR to only the data variables. Previous DSGE models, Leeper and Sims (1994) for example, fits the data worse than unrestricted VAR models.

There are 30 free parameters in the DSGE model and its likelihood value at the best fit is 2775. A first-order reduced-form VAR is estimated with a constant term and a time trend. Its maximum likelihood value is 2790 and it has 34 free parameters.[77] According to the likelihood criterion, the DSGE model forecasts only 0.9% worse than the VAR.[78]

The time series charts in Figure 3 compare the residuals of the DSGE model with the innovations from the VAR with a time trend. Overall, the DSGE model predicts no better than the VAR, but it does nearly as well and is superior over certain time ranges. If we compare the performance over each decade by averaging the residuals, the DSGE model does worse in the 1960s, better in the 1970s, about as good in the 1980s, and again worse in the 1990s.

The chart does not contain the residuals for the first three periods corresponding to the first year of the data.[79] The DSGE model does especially worse than the VAR in those early unreported periods, which is a generic problem when fitting a DSGE model. This is because a DSGE model implies an infinite order VAR for the data variables. Therefore, it is difficult to explain the movements with a few previous observations. In other words, since our data vector does not include all the variables of the DSGE model, the first observation does not capture either short run or long run information completely. Note also that the likelihood is defined conditional on

[77] There are 4 constants, 4 time trends, 16 coefficients, and 10 free elements in the covariance matrix of the innovations.

[78] The maximum likelihood value of a VAR without a time trend is the same as that of the DSGE model. The VAR has 30 free parameters. What is more, if the likelihood is defined conditional on -10*th* period (10 periods before the sample), the DSGE model performs better than the two VARs. See the following table for the exact likelihood values. Meanwhile, model selection criteria which penalize the number of parameters produce similar results. Three criteria are used: Akaike information criterion, Hannan-Quinn criterion, and Schwarz criterion.

observation conditioned on	DSGE	VAR with a trend	VAR without a trend
the 1st observation	2775	2790	2775
the -10th observation	2786	2756	2778

[79] Recall that the data series start at 1959:I. Since the likelihood is conditional on the first observation, the predictions start at 1959:II.

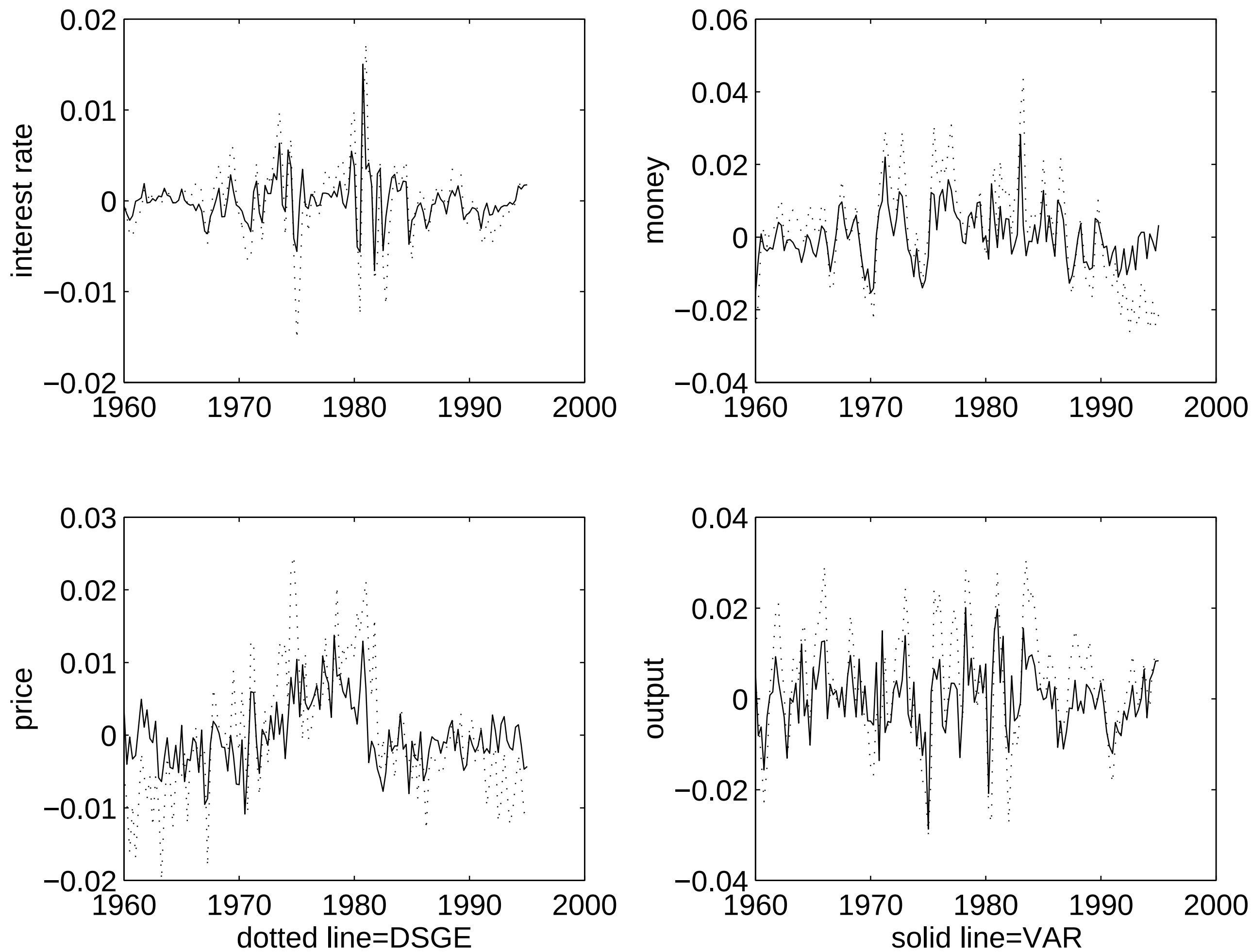

Figure 3: **Prediction Errors of the DSGE and the VAR***

* Reported are the residuals in the percentage terms.

the first observation. In a first-order VAR where all variables are available in the data, the first observation captures both information precisely.

Table 7: **Forecast Standard Deviations**

standard deviation	r	M	P	Y
The DSGE model	0.00256	0.00673	0.00422	0.00797
The VAR with a trend	0.00247	0.00740	0.00417	0.00686
The VAR without a trend	0.00259	0.00752	0.00426	0.00693

For convenience, Table 7 reports the Cholesky decomposition of the covariance matrices, which enables comparisons by variable across the models.[80] The ordering of the variables for Cholesky decomposition is (r, M, P, Y). The reported elements are interpreted as the standard deviation of the one-step-ahead forecast errors.[81] The DSGE model improves on the VAR with a time trend only for money. Compared with the VAR without a time trend, the DSGE model improves on the interest rate, money and price. The DSGE model captures the movement of the nominal variables pretty well. Overall, we daresay that the DSGE model explains the movements of the nominal variables relatively better than those of the real variables.

Another way to assess the fit is the steady state of the model with the means of the data. The estimated parameters imply a steady state that matches the means of the detrended data in some but not all aspects, as reported in Table 8. The steady state of the interest rate is different from the mean by less than 1%. The steady states of money and output are lower than their means since much of their movements are explained by persistent shocks.[82] This is consistent with the fact that the steady state of the price level is higher than the mean by 9%.

For the model's implications to be credible, the estimates must produce sensible dynamic responses to the exogenous shocks. Before computing the impulse responses and the variance decompositions, one must decide how to treat the covariation in any two innovations. In my model, there is only one covariation: the technology shock, ε_{At}, and the fixed-cost shock, $\varepsilon_{\Phi t}$. To make the case that monetary policy disturbances have an important effect on real aggregate activity, I make the technology

[80] Reported are the diagonal elements of the Cholesky decompositions. Since the VAR is unrestricted, the maximum likelihood covariance matrix is the same as the sample covariance matrix formed by the innovations. However, since the DSGE model corresponds to a restricted VAR, those two covariance matrices need not match in the case of the DSGE model. Also, there is a problem of which information should the forecast be conditioned on. In this paper, the maximum likelihood covariance matrix is used to form the covariance matrix of the data.

[81] See Kim (1995) for more discussion on this point.

[82] See the graphs plotting the percentage deviations of the data in Figure 6. The plots for money and output are steadily increasing.

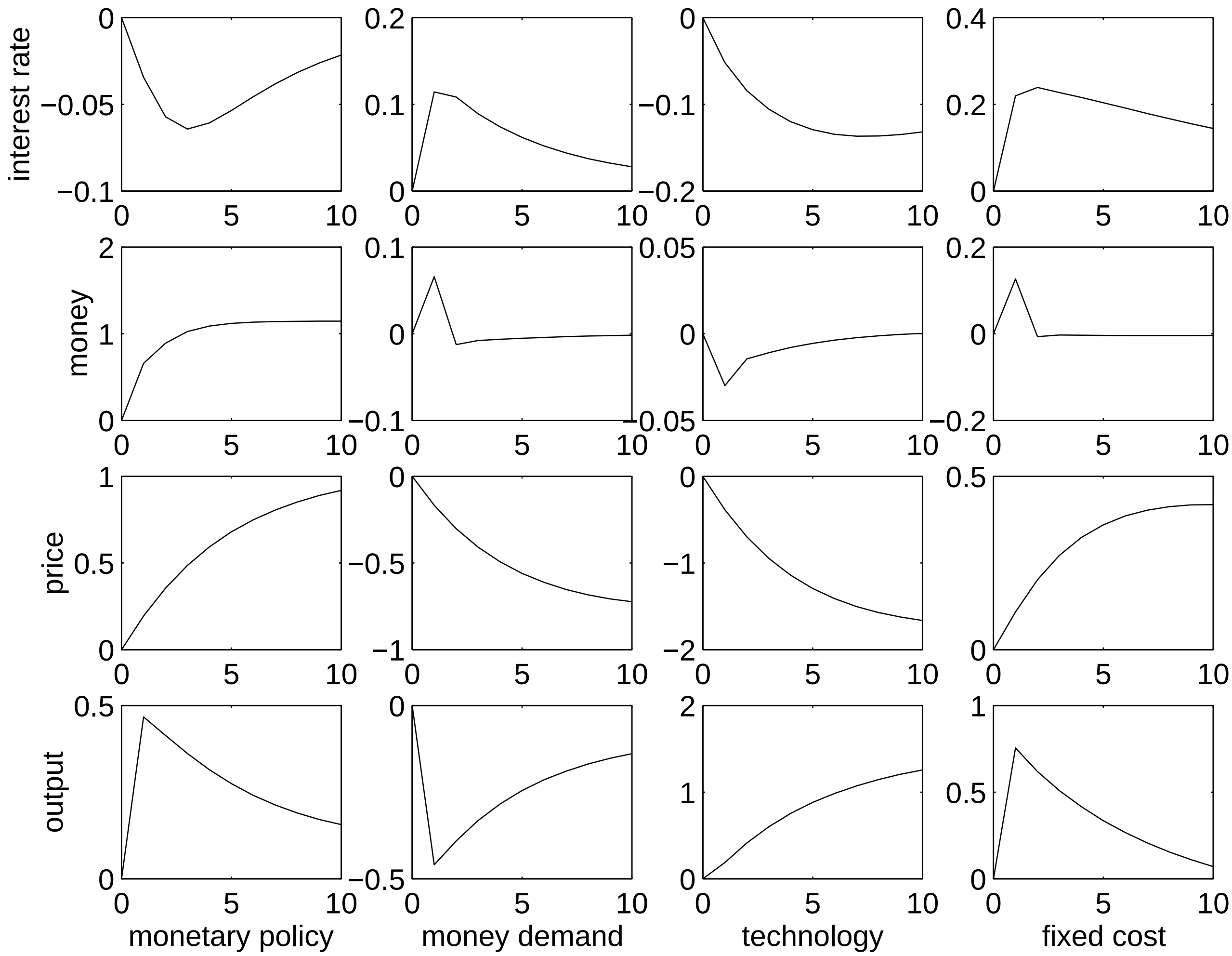

Figure 4: **Impulse Responses at the Estimated Parameters***
* The responses are with respect to one-standard-deviation shocks.

Table 8: **Data Means and the Steady State**

	interest rate	money	price	output
U.S. data means	1.0166	2.869	24.367	19.610
Model steady state	1.0259	2.444	26.752	16.231

shock as important as possible. For this purpose, the technology shock is assumed to be ordered before the fixed-cost shock. This ordering implies that an innovation in technology affects not only the technology shock but also the fixed-cost shock.

Figure 4 reports the impulse responses evaluated at the estimated parameters. All responses are with respect to a temporary shock of one standard deviation. The first column corresponds to the responses to a positive monetary policy shock. We can find the liquidity effect in the response of the interest rate and also the output effect in the response of output. The autocorrelation of the shocks causes the movement of money to be smooth and the nominal rigidities are a source of slow adjustment of prices.

The next three columns correspond to the other shocks. A positive money demand shock moves the interest rate up and so output down. A positive technology shock decreases the interest rate. This is mainly because the technology shock is negatively correlated with the fixed-cost shock. A positive fixed-cost shock moves the interest rate up since it is accompanied by an increase in expected inflation. Expected inflation is a source of positive movement of output.

3.5 Variance Decompositions

Once estimated, the model can be used to evaluate the underlying exogenous sources of fluctuations over the sample period. The fraction of the variance attributable to each shock is readily computed from the solution, (36), evaluated at the estimated parameters. In the following four tables, the variances of the interest rate, money, price, and output are decomposed into the fractions that are explained by the shocks in monetary policy, money demand, technology, and fixed cost.[83] The percentages of each variable's forecast error variance due to the four shocks are reported for several forecast horizons. The report is both in the short and medium runs: from 1 to 5 quarters, 10 quarters, and 20 quarters. The first line of Table 9 can be read as

[83]Impulse responses and variance decompositions let us analyze only the overall effects of the shocks. In contrast, historical decompositions allow us to understand the role of the shocks period by period. By historical decompositions, the unanticipated movements are attributed to each structural disturbance at each date, so that the proportion of monetary policy shock explaining the forecast errors at each date is calculated.

follows: 2% of the variance of the interest rate is explained by the monetary policy shock when the forecast horizon is 1 quarter and 3% is explained by the shock when the forecast horizon is 2 quarters. Note that the four numbers in each column add up to 100%.

Table 9: **Interest Rate Decompositions**

INTEREST RATE	1	2	3	4	5	10	20
monetary policy	.02	.03	.04	.04	.04	.03	.03
money demand	.20	.17	.15	.13	.12	.08	.06
technology	.04	.07	.10	.12	.15	.24	.32
fixed cost	.74	.73	.71	.70	.70	.64	.59

Table 9 gives the results for interest rate decompositions. The fixed-cost shock accounts for more than 70% of interest rate movement in the short run. As the forecast horizon lengthens, its importance decreases but is still more than 50%. This is partly because the fixed-cost shock strongly affects expected inflation. An intuitive explanation is that the increase in fixed cost is reflected in the price level slowly over time and that this causes inflation. The second most important shock depends on the forecast horizon. It is the shock in money demand in the short run, and the technology shock in the medium run. The shock in monetary policy does not seem to be important for the movement of the interest rate.[84] Including a feedback mechanism of the real activities in the monetary policy reaction function would make monetary policy more important. Under the new specification, the technology and fixed-cost shocks account for less of interest rate movement since part of the old propagation is endogenized by the feedback of the real activities. This conjecture is confirmed by calibrating the parameter representing the sensitivity of the feedback.

Table 10 shows that the movement of the money stock is almost entirely due to the shock in monetary policy. Even if money is endogenous in principle, the degree of the endogeneity is very small. Other shocks play little roles. The variance decomposition of money in my model is quite different from the results in the structural VAR literature, where the shock in money demand plays an important role. Here, the money demand shock does not contribute at all, even if its variance is large relative to the variance of the monetary policy shock.

[84] Therefore, my model is immune to the potential criticism that it captures the movement of the interest rate mainly because of the complicated specification of monetary policy. Even if my specification of monetary policy is important in generating a realistic behavior of the interest rate, the variance decomposition shows that monetary policy is not a key determinant of the interest rate movement.

Table 10: **Money Decompositions**

MONEY	1	2	3	4	5	10	20
monetary policy	.95	.98	.99	.99	.99	.99	.99
money demand	.01	.00	.00	.00	.00	.00	.00
technology	.00	.00	.00	.00	.00	.00	.00
fixed cost	.04	.02	.01	.01	.00	.00	.00

Table 11: **Price Decompositions**

PRICE	1	2	3	4	5	10	20
monetary policy	.17	.17	.17	.17	.18	.19	.20
money demand	.12	.12	.12	.12	.12	.12	.12
technology	.66	.65	.65	.65	.65	.65	.64
fixed cost	.05	.05	.05	.05	.05	.05	.05

The most important factor for price movements is the technology shock, which explains steadily over 60% as shown in Table 11. The shock in monetary policy explains 15-20% and the shock in money demand explains 12% of price movement. Fixed cost has some effect, 5%, on price movements. Here again, the new specification of monetary policy including the feedback of real activities increases the importance of the monetary policy shock. Note that the variable decomposed is the price level, not the inflation rate. For the inflation movement, the fixed-cost shock is an important factor.

Table 12: **Output Decompositions**

OUTPUT	1	2	3	4	5	10	20
monetary policy	.21	.20	.19	.17	.15	.07	.03
money demand	.20	.19	.17	.15	.13	.07	.03
technology	.03	.11	.20	.31	.41	.72	.89
fixed cost	.55	.50	.44	.38	.32	.14	.05

Table 12 reports that the fixed-cost shock explains 40-55% of output fluctuations in the short run. If the technology and fixed-cost shocks are combined and called supply shocks, these explain less than 70%, if the forecast horizon is less than 1 year. However, in the medium run, the technology shock accounts for 70-90% of output fluctuations.[85] In the short run, the shock in monetary policy and the shock

[85] Compare my results on short and medium runs with the conclusion in Prescott (1986) that technology shocks account for 75% of business cycles.

in money demand are also important in understanding output fluctuations. Each explains 15-20% of output movements in the short run, but much less in the medium run. This variance decomposition of output is similar to the results of the structural VAR literature.

3.6 Cyclical Implications

It is standard in the RBC literature to focus on the summary statistics describing relative volatility of the series and their correlation with output. The formal maximum likelihood estimation procedure obviously does not place all of the weight on this small set of statistics, so it is worthwhile to see what the parameter estimates imply for these commonly studied statistics. Therefore, the standard deviations and the contemporaneous correlations of the model forecasts are computed and compared with those of the data.[86] The tth period model forecasts are conditioned on the sample up to $t-1$, and the parameters are set to the full-sample maximum likelihood estimates. Both the model and data series are logged and differenced before calculation, so these statistics are in percentage terms.[87]

Table 13 shows that the standard deviation of output forecasted by the model exactly matches that of the data. For the other three variables, the standard devia-

Table 13: **Contemporaneous Second Moments**

model forecast (data)	interest rate	money	price	output
interest rate	0.0034 (0.0026)	-0.3918	0.3753	0.0198
money	(-0.1276)	0.0097 (0.0086)	0.0866	0.1524
price	(0.0954)	(0.0231)	0.0099 (0.0066)	-0.4229
output	(0.3488)	(0.1360)	(-0.2455)	0.0089 (0.0089)

[86]An alternative way is to calculate the second moments of the simulated series and to compare them with those of the data, which is more conventional in the RBC literature.

[87]If the series are logged and detrended, the correlation of money and output is negative and that of money and the interest rate is positive, for both the data and the model forecasts. This is incompatible with the cyclical implications from the two effects of monetary policy, so I compare the statistics of the logged and differenced series here. Log-differencing is also adopted in King and Watson (1995).

tions of the model forecasts are larger than those from the data. The absolute values of the correlations of the model forecasts are also higher, except for the interest rate and output pair. One possible reason is that the variables are highly persistent even after logarithmic differencing and that the estimation may be fitting this feature at the cost of fitting higher frequencies. Overall, the model matches all the signs of the second moments. Considering that the estimation procedure is designed to fit all aspects of the data, it is not obvious *ex ante* how well the estimates are able to match the small set of statistics.[88]

King and Watson (1995) analyze the nominal features of business cycles with three different DSGE models.[89] While the models have diverse successes and failures, none can account for the fact that the nominal and real interest rates are "inverted leading indicators" of real economic activity. That is, none of their three models captures the U.S. business cycle fact that a high nominal or real interest rate in the current quarter predicts a decrease of real economic activity two to four quarters in the future.[90] To see if my model improves on that perspective, serial correlation coefficients between interest rate and output are computed.[91]

Table 14 shows that my model fits the property of the data that the nominal interest rate is an inverted leading indicator. The serial correlation coefficients from the model reproduce the pattern of the data that an increase in the interest rate in the current period predicts a decrease of output two to six quarters in the future.

3.7 Policy Experiments

We analyze four experiments in monetary policy. Two regimes of monetary policy are considered. Under each regime, fiscal policy is also modified so that the economy exhibits a unique equilibrium. The first regime, called an M-policy, is one in which

[88] Using the linear trends, I do not report the comparison with other models. Applying Hodrick-Prescott filtering to the model-generated data, the four data variables in my model performs better than those in other DSGE models.

[89] The three models are a "real business cycle" model, a "sticky price" model, and a "liquidity effect" model. Their "sticky price" model is theoretically similar to the model presented in this paper. However, its empirical implications are rather different, mainly because of a different specification of monetary policy. Their "liquidity effect" model is usually called a limited participation model.

[90] This fact is consistent with the evidence presented in Bernanke and Blinder (1992).

[91] Here the results only for the nominal interest rate are calculated, since there is no data for expected inflation rate. Using the expected inflation rates generated from the DSGE model, I also find that my model fits the idea that the real interest rate is also an inverted leading indicator. King and Watson (1995) calculate the correlations from the estimated spectral density matrix, using only the business cycle (6-32 quarters) frequencies. However, a different method of detrending is hardly likely to change the results.

Table 14: **Serial Correlations between Interest Rate and Output**

$Corr\,(\Delta \log r_t, \Delta \log Y_{t+d})$						
d(quarters)	1	2	3	4	5	6
data	0.072	-0.297	-0.188	-0.209	-0.198	-0.177
model	0.042	-0.177	-0.173	-0.193	-0.153	-0.109

the monetary authority controls only the stock of money: the elasticity of money growth to the interest rate in the policy function, ν, is set to zero. The second regime, called an r-policy, is one in which the monetary authority controls only the interest rate and it corresponds to the specification that $\nu = \infty$.[92] All other coefficients except ν stay at the value of maximum likelihood estimates. Note that the value of ν does not affect the steady state. Each regime shift can be implemented in two alternative ways: expected and unexpected. In the first case, the change in policy is perceived by the private agents of the economy so they correspondingly change their expectations. In the second case, the change is not perceived by the private agents so they do not change their expectations.[93] Since the policy experiments are based upon optimizing behavior from a model with deep parameters, they are not subject to the criticisms from the Lucas critique.[94] The experiments focus on how the regime shift changes the mechanism through which technology shocks are transmitted, and so are not a fully fledged welfare analysis. However, such analysis gives insight to the welfare analysis and has never been done. For this purpose, impulse responses to a one standard deviation technology shock are drawn and compared with those from the estimated model.[95]

The first two columns of Figure 5 concern an M-policy. If the change of the policy is unexpected (the second column), the responses to the technology shock are very similar to those before the change. One minor difference is that money returns to the steady state faster than before the policy change. This is because

[92]The economy with an r-policy is not a version of Ricardian equivalence, since fiscal policy affects variables other than tax and debt through the expectation of future prices. See Sims (1994) on this point.

[93]Algebraically, the first one is to change ν in the policy equation and then to obtain the solution from scratch. The second is to solve the equilibrium equations under the old policy regime and then to substitute the new policy equation for the old one, without changing the other equations of the equilibrium.

[94]Recent structural VAR models, Cochrane (1995) and Sims and Zha (1995) for example, extract policy-invariant identifying assumptions from optimizing behavior. This is partly meant to avoid the Lucas critique.

[95]Variance decompositions are irrelevant for policy experiments, since the variance of the monetary policy shock cannot be determined in a plausible way.

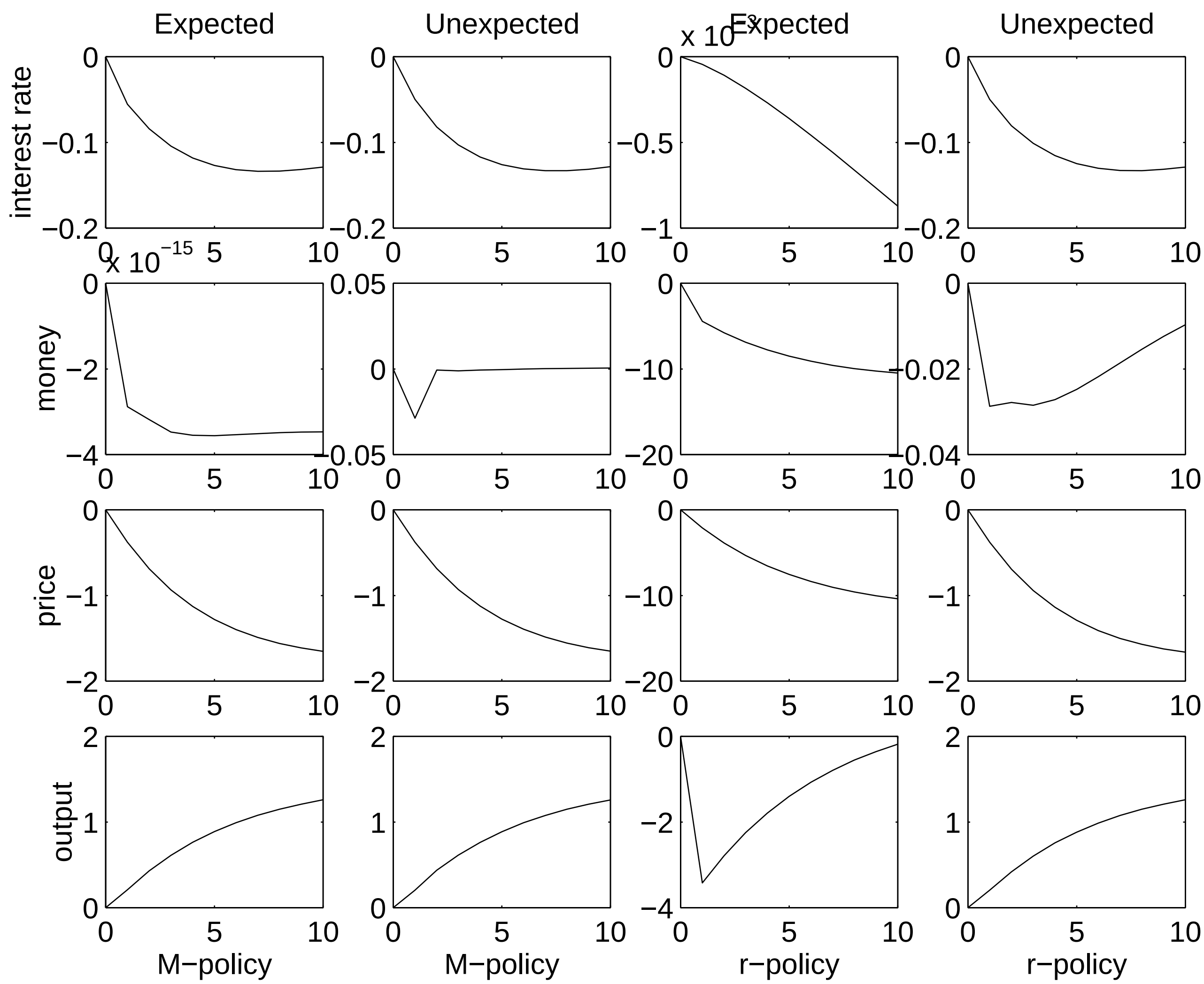

Figure 5: **Policy Experiments***
* The responses are with respect to a one-standard-deviation technology shock under a new policy regime.

money does not respond to the interest rate. If the policy change is expected (the first column), the responses to the technology shock are also very similar to those before the policy change. Of course, money stays at the steady state.[96] These two experiments show that there is little effect of changing into an M-policy, based on the parameter estimates. Note that an M-policy corresponds to the specification of exogenous money supply. This suggests that the endogeneity of money does not have a big influence on the responses to the technology shock at the estimated parameters, even if important for the propagation of monetary policy.

The two right columns of Figure 5 are the responses under the r-policy regime. If the change is unexpected (the fourth column), the responses are again similar, except that money returns to the steady state very slowly. The response of money is sluggish because the amount of money is not controlled by the monetary authority. If the change is expected (the third column), the responses are drastically different. The interest rate does not move, of course.[97] Money and prices fluctuate wildly and are very unstable. They decrease by around 10% after 10 quarters and these fluctuations are much larger than those found in any other experiment. Output does not increase but decreases after the positive technology shock, due to the fact that money decreases faster than prices. This suggests that an appropriate choice of the sensitivity-to-interest-rate parameter, ν, can remove the output fluctuations due to the technology shock. Unlike an M-policy, the effect of changing into an r-policy is quite sizable, especially if the change is expected.[98]

To summarize, the model can be used to analyze a wide variety of policy issues.[99] Changes of monetary policy can only be analyzed seriously in a model that features an explicit transmission mechanism of the policy. The DSGE model in this paper is an example.

4 Conclusion

Previous work using a flexible-price, competitive DSGE model has provided reasonable descriptions of the data on real variables. However, such work has not captured the nominal features of business cycles well. Typically, expansionary monetary policy produces neither a positive response of aggregate output nor a negative response

[96] Note that there is a scale factor of 10^{-14} in the response of money.

[97] Note that there is also a scale factor in the response of the interest rate and that ν is set not to infinity but to a very large number in the computation.

[98] Using the structural VAR framework, Sims and Zha (1995) experiment the changes to an M-policy and an r-policy. They also find that the change into an M-policy has moderate effects on output fluctuations while the change into an r-policy has substantial effects.

[99] See Dow (1995) for an example of monetary stabilization policy.

of interest rates.

This paper aims at filling this gap with a DSGE model extended to allow for real and nominal rigidities. Four shocks, including both technology and monetary policy shocks, affect the economy. The exercise with several restricted versions of the model shows that both real and nominal rigidities are necessary to produce reasonable impulse responses to the shock in monetary policy. In order to select the magnitude of the effects of monetary policy in a data-dependent manner, the model is estimated using maximum likelihood on U.S. data. The estimated model exhibits reasonable impulse responses and its forecasts produce the second moments similar to those of the data. As a by-product, it also reproduces the fact that an increase of interest rates in the current period predicts a decrease of real economic activity two to six quarters in the future, a feature of U.S. business cycles which has never been captured by previous research using DSGE models.

It would be interesting to estimate the model for a sub-period and to see how well the estimated model explains the out-of-sample data. This is particularly interesting since monetary policy regimes are said to have changed several times, e.g. the October 1979 Volker disinflation. It would be more helpful to randomize the policy regimes.

For further research, adding more structure into the model and using more data for estimation are likely to produce a better-behaving estimated model. For instance, one may notice that the parameter for real rigidities, ϕ_K, is very sharply estimated. Thus, there may well be enough information in the data to enable estimating a more general form of adjustment costs for capital.[100] Also, more real variables need to be included in the data to pin down the sources of the volatility of real variables. Since this paper deals with only four variables as the data and three out of the four are nominal variables, it would be particularly interesting to add more real variables in the estimation and to see how well this model can explain the additional variables.[101]

[100] The most general form is $\mathrm{AC}_{it}^K = \frac{\phi_K}{2(1+\varepsilon_1)} \left[\left(\frac{I_{it}}{K_{it}^{\varepsilon_2}} - \varepsilon_3 \right)^2 \right]^{(1+\varepsilon_1)} I_{it}$, where three ε's are nonnegative.

[101] The interesting features to investigate are the cyclicality of real wages and the volatility of investment and labor. The modifications in this paper, real and nominal rigidities, may have improved or deteriorated the performance of DSGE models along these dimensions.

A Appendix

A.1 The Data

The following time series are extracted from the Citibase database.

Series	Title
fyff	Interest Rate: Federal Funds (Effective) (% per annum, NSA)
fm2	Money Stock: M2 (Bil. $)
gd	Implicit Price Deflator: Gross National Product
gnpq	Gross National Product (Bil. 1987$) (T.1.6)
p16	Population: Total Civilian Noninstitutional (Thous., NSA)

The variables of the models are defined as follows.

$$\begin{aligned} r_t &= 1 + \left(\frac{\texttt{fyff}}{400}\right), \\ M_t &= 1000 \times \left(\frac{\texttt{fm2}}{\texttt{p16}}\right), \\ P_t &= \texttt{gd}, \\ Y_t &= 1000 \times \left(\frac{\texttt{gnpq}}{\texttt{p16}}\right). \end{aligned}$$

A.2 Derivatives and Elasticities

The formulæ for the derivatives and the elasticities are as follows.

$$\begin{aligned} U_{it} &= U(C_{it}, M_{it}/P_t, L_{it}), \\ \frac{\partial U}{\partial C_{it}} &= \frac{(1-\sigma_1)\, U_{it} a C_{it}^{-1/\sigma_2}}{(C_{it}^*)^{(\sigma_2-1)/\sigma_2}}, \\ \frac{\partial U}{\partial M_{it}} &= \frac{(1-\sigma_1)\, U_{it} ab \left(\frac{M_{it}}{P_t}\right)^{-1/\sigma_2} \frac{1}{P_t}}{(C_{it}^*)^{(\sigma_2-1)/\sigma_2}}, \\ \frac{\partial U}{\partial L_{it}} &= \frac{-(1-\sigma_1)\, U_{it}\,(1-a)}{(1-L_{it})}. \end{aligned}$$

$$e_{it}^L = \theta_L \left[\begin{array}{c} 1 - \frac{\phi_L W_t}{L_{it}} \left(\frac{P_t W_{it}}{P_{t-1} W_{i,t-1}} - \mu\right) \frac{P_t}{P_{t-1} W_{i,t-1}} + \\ \beta \frac{\phi_L W_t}{L_{it}} \mathrm{E}_t \left[\left(\frac{P_{t+1} W_{i,t+1}}{P_t W_{it}} - \mu\right) \left(\frac{P_{t+1} W_{i,t+1}}{P_t W_{it}^2}\right) \frac{\Lambda_{t+1}}{\Lambda_t} \right] \end{array} \right]^{-1},$$

$$e_{jt}^Y = \theta_Y \left[\begin{array}{c} 1 - \frac{\phi_Y Y_t}{Y_{jt}} \left(\frac{P_{jt}}{P_{j,t-1}} - \frac{\mu}{G}\right) \frac{P_t}{P_{j,t-1}} + \\ \frac{\phi_Y Y_t}{Y_{jt}} \mathrm{E}_t \left[\frac{\rho_{t+1}}{\rho_t} \left(\frac{P_{j,t+1}}{P_{jt}} - \frac{\mu}{G}\right) \left(\frac{P_{t+1} P_{j,t+1}}{P_{jt}^2}\right) \right] \end{array} \right]^{-1}.$$

$$
\begin{aligned}
u_t &= U(c_t, m_t/p_t, L_t), \\
\frac{\partial u}{\partial c_t} &= \frac{(1-\sigma_1)\, u_t a c_t^{-1/\sigma_2}}{(c_t^*)^{(\sigma_2-1)/\sigma_2}}, \\
\frac{\partial u}{\partial m_t} &= \frac{(1-\sigma_1)\, u_t a b \left(\frac{m_t}{p_t}\right)^{-1/\sigma_2} \frac{1}{p_t}}{(c_t^*)^{(\sigma_2-1)/\sigma_2}}, \\
\frac{\partial u}{\partial L_t} &= \frac{-(1-\sigma_1)\, u_t (1-a)}{(1-L_t)}.
\end{aligned}
$$

A.3 The Equilibrium

The first set of equations describing the equilibrium comes from the problem of the households.

$$
\begin{aligned}
\mathrm{AC}_t^L &= \frac{\phi_W}{2}\left(\frac{P_t W_t}{P_{t-1}W_{t-1}} - \mu\right)^2 W_t, \\
C_t &= W_t L_t + Z_t K_t + \Pi_t - \mathrm{AC}_t^L - I_t\left(1 + \frac{\phi_K}{2}\left(\frac{I_t}{K_t}\right)^2\right), \\
K_t &= I_{t-1} + (1-\delta) K_{t-1}, \\
\Lambda_t &= \frac{\partial U}{\partial C_t}, \\
r_t^{-1} &= 1 - b_t \left(\frac{P_t C_{it}}{M_{it}}\right)^{1/\sigma_2}, \\
e_t^L &= \theta_L \left[\begin{array}{c} 1 - \frac{\phi_W}{L_t}\left(\frac{P_t W_t}{P_{t-1}W_{t-1}} - \mu\right)\frac{P_t W_t}{P_{t-1}W_{t-1}} + \\ \beta \frac{\phi_W}{L_t} \mathrm{E_t}\left[\left(\frac{P_{t+1}W_{t+1}}{P_t W_t} - \mu\right)\left(\frac{P_{t+1}W_{t+1}}{P_t W_t}\right)\frac{\Lambda_{t+1}}{\Lambda_t}\right] \end{array}\right]^{-1}, \\
\frac{\partial U}{\partial L_t} &= -W_t \Lambda_t \left(1 - \frac{1}{e_t^L}\right), \\
0 &= \left(Z_t + \phi_K \left(\frac{I_t}{K_t}\right)^3\right)\Lambda_t - Q_t + \beta(1-\delta)\mathrm{E_t}\left[Q_{t+1}\right], \\
0 &= \Lambda_t\left(1 + \frac{3\phi_K}{2}\left(\frac{I_t}{K_t}\right)^2\right) - \beta \mathrm{E_t}\left[Q_{t+1}\right], \\
\frac{\Lambda_t}{P_t} &= \beta r_t \mathrm{E_t}\left[\frac{\Lambda_{t+1}}{P_{t+1}}\right], \\
\log(b_t) &= \rho_b \log(b_{t-1}) + (1-\rho_b)\log(b) + \varepsilon_{bt}.
\end{aligned}
$$

The second set comes from the problem of the firms.

$$\begin{aligned}
Y_t &= A_t \left(K_t^{\alpha}(g^t L_t)^{1-\alpha}\right)^{\gamma} - \Phi_t G^t, \\
\log(A_t) &= \rho_A \log(A_{t-1}) + (1-\rho_A)\log(A) + \varepsilon_{At}, \\
\log(\Phi_t) &= \rho_\Phi \log(\Phi_{t-1}) + (1-\rho_\Phi)\log(\Phi) + \varepsilon_{\Phi t}, \\
\mathrm{AC}_t^P &= \frac{\phi_P}{2}\left(\frac{P_t}{P_{t-1}} - \frac{\mu}{G}\right)^2 Y_t, \\
\Pi_t &= Y_t - Z_t K_t - W_t L_t - \mathrm{AC}_t^P, \\
e_t^Y &= \theta_Y \left[\begin{array}{c} 1-\phi_P\left(\frac{P_t}{P_{t-1}} - \frac{\mu}{G}\right)\frac{P_t}{P_{t-1}} + \\ \beta\phi_P \mathrm{E_t}\left[\frac{\Lambda_{t+1}}{\Lambda_t}\left(\frac{P_{t+1}}{P_t} - \frac{\mu}{G}\right)\left(\frac{P_{t+1}}{P_t}\right)^2\right]\end{array}\right]^{-1}, \\
Z_t K_t &= \gamma\alpha\left(Y_t + \Phi_t G^t\right)\left(1 - \frac{1}{e_t^Y}\right), \\
\alpha W_t L_t &= (1-\alpha) Z_t K_t.
\end{aligned}$$

The third set comes from the behavior of the government, with two equations for the budget constraint and fiscal policy deleted.

$$\begin{aligned}
\frac{M_t}{M_{t-1}} &= \left(\frac{M_{t-1}}{M_{t-2}}\right)^{\rho_M} \mu^{1-\rho_M}\mu_t \left(\frac{r_t r_{t-1}^{-(\rho_r+\rho_R)} r_{t-2}^{\rho_r \rho_R}}{r^{(1-\rho_r)(1-\rho_R)}}\right)^{\nu}, \\
\log \mu_t &= \rho_\mu \log \mu_{t-1} + \varepsilon_{\mu t}.
\end{aligned}$$

A.4 Steady State

Non-trivial steady-state values are as follows. In what follows, δ_G replaces $(\delta + (G-1))$ to save space.

$$\begin{aligned}
\bar{r} &= \beta_G^{-1}\left(\frac{\mu}{G}\right), \\
\bar{Z} &= \left(\frac{1-\beta_G(1-\delta)}{\beta_G}\right)\left(1 + \frac{3}{2}\phi_K \delta_G^2\right) - \phi_K \delta_G^3, \\
\frac{\bar{c}}{\bar{y}} &= 1 - \frac{\alpha}{\bar{Z}}\delta_G\left(1 + \frac{\phi_K}{2}\delta_G^2\right), \\
\frac{\bar{L}}{1-\bar{L}} &= \frac{(1-\alpha)\left(1 - \frac{1}{\theta_L}\right)\frac{a}{1-a}}{\frac{\bar{c}}{\bar{y}}\left[1 + \frac{b^{\sigma_2}}{(1-\bar{r}^{-1})^{\sigma_2 - 1}}\right]}, \\
\bar{y}^{1-\alpha\gamma} &= A\gamma\left(1 - \frac{1}{\theta_Y}\right)\left(\left(\frac{\alpha}{\bar{Z}}\right)^{\alpha}\bar{L}^{1-\alpha}\right)^{\gamma},
\end{aligned}$$

$$\begin{aligned}
\bar{k} &= \left(\frac{\alpha}{\bar{Z}}\right)\bar{y}, \\
\bar{i} &= \delta_G \bar{k}, \\
\bar{w} &= \left(\frac{1-\alpha}{\bar{L}}\right)\bar{y}, \\
\bar{p} &= \frac{\bar{m}}{\bar{c}}\left[\frac{1}{b}\left(1-\bar{r}^{-1}\right)\right]^{\sigma_2}, \\
\bar{c}^* &= \left(\bar{c}^{(\sigma_2-1)/\sigma_2} + b\left(\frac{\bar{m}}{\bar{p}}\right)^{(\sigma_2-1)/\sigma_2}\right)^{\sigma_2/(\sigma_2-1)}, \\
\bar{u} &= \frac{\left((\bar{c}^*)^a\left(1-\bar{L}\right)^{1-a}\right)^{1-\sigma_1}}{1-\sigma_1}, \\
\bar{\lambda} &= \frac{(1-\sigma_1)\,\bar{u}a\bar{c}^{-1/\sigma_2}}{(\bar{c}^*)^{(\sigma_2-1)/\sigma_2}}, \\
\bar{q} &= \frac{\bar{\lambda}}{\beta_G}\left(1+\frac{3\phi_K}{2}\delta_G^2\right).
\end{aligned}$$

A.5 Log-linearization

First, I have two definitional equations.

$$\hat{f}_t = \hat{p}_t - \hat{p}_{t-1}, \tag{38}$$

$$\hat{v}_t = \hat{w}_t - \hat{w}_{t-1}. \tag{39}$$

Second, the following equations come from the problem of the households. Due to the above two definitional equations, the problem can be written as an VAR(1) form.

$$\begin{aligned}
\left(\frac{\bar{c}}{\bar{y}}\right)\hat{c}_t &= (1-\alpha)\left(\hat{w}_t + \hat{L}_t\right) + \alpha\left(\hat{k}_t + \hat{Z}_t\right) + \frac{\pi_t}{\bar{y}} \\
&\quad - \left(\frac{\bar{i}}{\bar{y}}\right)\left(1+\frac{3}{2}\phi_K\delta_G^2\right)\hat{i}_t + \left(\frac{\bar{k}}{\bar{y}}\right)\phi_K\delta_G^3\hat{k}_t,
\end{aligned} \tag{40}$$

$$G\hat{k}_t = \delta_G\hat{i}_{t-1} + (1-\delta)\,\hat{k}_{t-1}, \tag{41}$$

$$\hat{u}_t = (1-\sigma_1)\left(a\hat{c}_t^* - (1-a)\frac{\bar{L}}{1-\bar{L}}\hat{L}_t\right), \tag{42}$$

$$\hat{c}_t^* = \left(\frac{\bar{c}}{\bar{c}^*}\right)^{(\sigma_2-1)/\sigma_2}\hat{c}_t + b\left(\frac{\bar{m}}{\bar{p}\bar{c}^*}\right)^{(\sigma_2-1)/\sigma_2}(\hat{m}_t - \hat{p}_t), \tag{43}$$

$$\hat{\lambda}_t = \hat{u}_t - \frac{1}{\sigma_2}\hat{c}_t - \frac{\sigma_2 - 1}{\sigma_2}\hat{c}_t^*, \tag{44}$$

$$\hat{r}_t = (\bar{r} - 1)\left(\hat{b}_t + \frac{\hat{p}_t + \hat{c}_t - \hat{m}_t}{\sigma_2}\right), \tag{45}$$

$$\hat{e}_{t-1}^L = \frac{\phi_W \mu^2}{\bar{L}}\left(\hat{f}_{t-1} + \hat{v}_{t-1}\right) - \beta_G \frac{\phi_W \mu^2}{\bar{L}} \mathrm{E}_{\text{t-1}}\left[\hat{f}_t + \hat{v}_t\right], \tag{46}$$

$$\hat{u}_t = \hat{w}_t + \hat{\lambda}_t + \frac{1}{\theta_L - 1}\hat{e}_t^L - \frac{\bar{L}}{1 - \bar{L}}\hat{L}_t, \tag{47}$$

$$\begin{aligned}\bar{q}\hat{q}_{t-1} &= \bar{\lambda}\left(\bar{Z}\hat{Z}_{t-1} + 3\phi_K \delta_G^3\left(\hat{i}_{t-1} - \hat{k}_{t-1}\right)\right) \\ &\quad + \left(\bar{Z} + \phi_K \delta_G^3\right)\bar{\lambda}\hat{\lambda}_{t-1} + \beta_G (1 - \delta)\,\bar{q}\mathrm{E}_{\text{t-1}}\left[\hat{q}_t\right],\end{aligned} \tag{48}$$

$$\beta_G \bar{q}\mathrm{E}_{\text{t-1}}\left[\hat{q}_t\right] = \left(1 + \frac{3\phi_K}{2}\delta_G^2\right)\bar{\lambda}\hat{\lambda}_{t-1} + 3\phi_K \delta_G^2 \bar{\lambda}\left(\hat{i}_{t-1} - \hat{k}_{t-1}\right), \tag{49}$$

$$\hat{\lambda}_{t-1} = \hat{r}_{t-1} + \mathrm{E}_{\text{t-1}}\left[\hat{\lambda}_t - \hat{f}_t\right], \tag{50}$$

$$\hat{b}_t = \rho_b \hat{b}_{t-1} + \varepsilon_{bt}. \tag{51}$$

Third, the following equations come from that of the firms. Again, γ_θ replaces $\gamma\left(1 - \frac{1}{\theta_Y}\right)$ to save space.

$$\gamma_\theta \hat{y}_t = \left(\hat{A}_t + \gamma\alpha\hat{k}_t + \gamma(1 - \alpha)\hat{L}_t\right) - \left[1 - \gamma_\theta\right]\hat{\Phi}_t, \tag{52}$$

$$\hat{A}_t = \rho_A \hat{A}_{t-1} + \varepsilon_{At}, \tag{53}$$

$$\hat{\Phi}_t = \rho_\Phi \hat{\Phi}_{t-1} + \varepsilon_{\Phi t}, \tag{54}$$

$$\pi_t / \bar{y} = \hat{y}_t - \alpha\left(\hat{Z}_t + \hat{k}_t\right) - (1 - \alpha)\left(\hat{w}_t + \hat{L}_t\right), \tag{55}$$

$$\hat{e}_{t-1}^Y = \phi_P \bar{f}^2 \hat{f}_{t-1} - \beta_G \phi_P \bar{f}^3 \mathrm{E}_{\text{t-1}}\left[\hat{f}_t\right], \tag{56}$$

$$\hat{Z}_t + \hat{k}_t = \gamma_\theta \hat{y}_t + \left[1 - \gamma_\theta\right]\hat{\Phi}_t + \frac{1}{\theta_Y - 1}\hat{e}_t^Y, \tag{57}$$

$$\hat{w}_t + \hat{L}_t = \hat{Z}_t + \hat{k}_t. \tag{58}$$

Fourth, government behavior is characterized as the following equations.

$$\begin{aligned}\hat{m}_t - \hat{m}_{t-1} &= \rho_M\left(\hat{m}_{t-1} - \hat{m}_{t-2}\right) + (1 + \nu)\,\hat{\mu}_t \\ &\quad + \nu\left(\hat{r}_t - (\rho_r + \rho_R)\,\hat{r}_{t-1} + \rho_r \rho_R \hat{r}_{t-2}\right),\end{aligned} \tag{59}$$

$$\hat{\mu}_t = \rho_\mu \hat{\mu}_{t-1} + \varepsilon_{\mu t}. \tag{60}$$

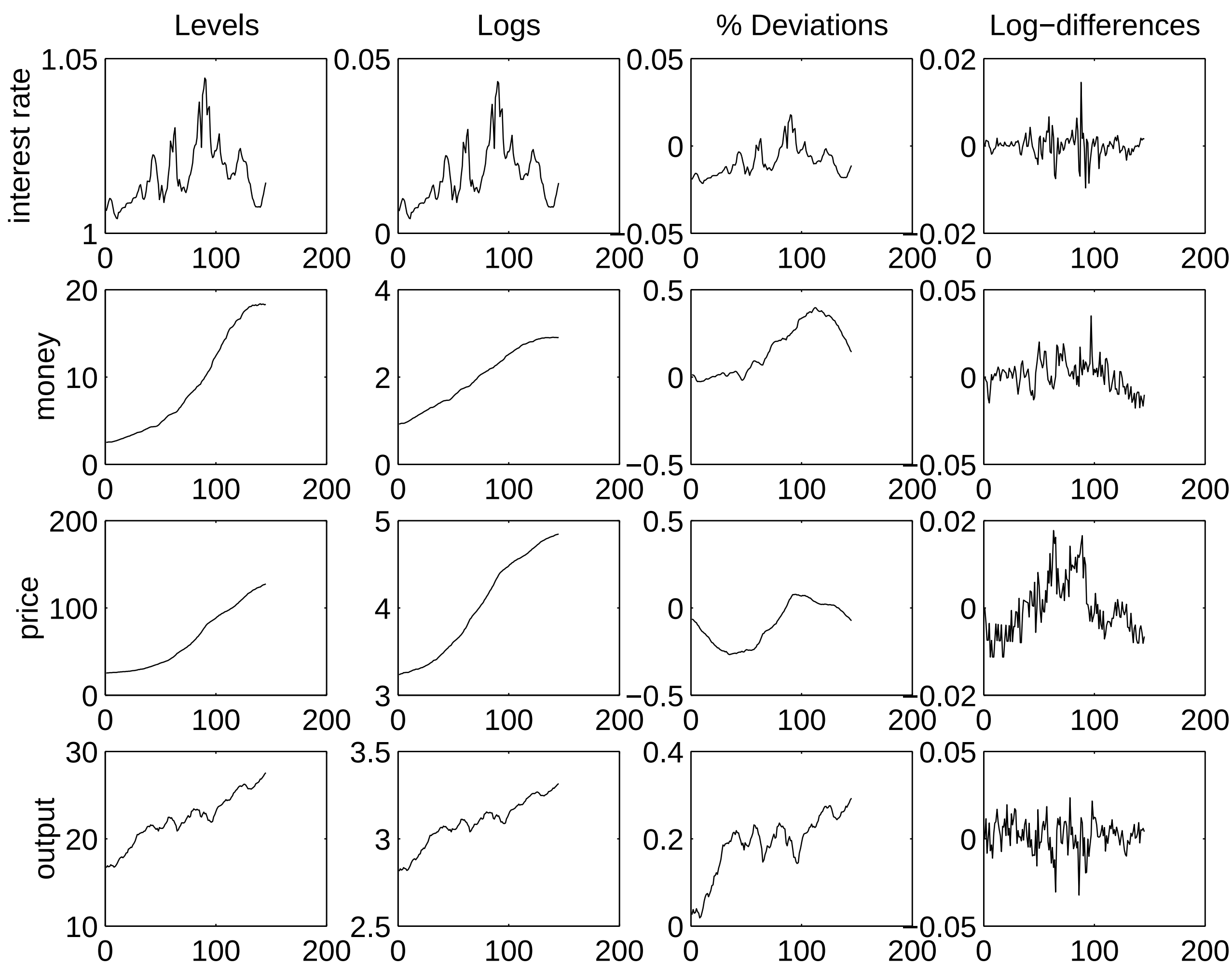

Figure 6: **Data Plots**

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